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ABSTRACT

Basic concepts of waste heat management on shallow and deep small water bodies and rivers are reviewed and examples are given. This study defines a small water body as a body in which the far field hydrothermal effects of a heated discharge can be detected in a major portion or practically all of the water body. Environmental effects due to warming of a small natural water body are consequently not limited to the immediate area of the outfall. The report divides small water bodies into three categories: rivers, nonstratified water bodies, and stratified water bodies. Management and control alternatives for each category are discussed, as well as the biological effects of various cooling systems, and methods for prediction and thermal modeling. Emphasis is placed on the significance of site-specific variations and the necessity for consideration of all alternatives before selection of a cooling system for a particular site. (Author/BB)

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HEATED DISCHARGE CONTROL AND MANAGEMENT ALTERNATIVES

Small Water Bodies and Rivers

by

James F. MacLaren Limited

for the

Water Pollution Control Directorate
Environmental Protection Service
FISHERIES AND ENVIRONMENT CANADA

Report No. EPS 3-WP-77-13
October 1977

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ABSTRACT

Basic concepts of waste heat management on shallow and deep small water bodies and rivers are reviewed and examples are given. This study defines a small water body as a body in which the far field hydrothermal effects of a heated discharge can be detected in a major portion or practically all of the water body. Environmental effects due to warming of a small natural water body are consequently not limited to the immediate area of the outfall. The report divides small water bodies into three categories: rivers, nonstratified water bodies, and stratified water bodies. Management and control alternatives for each category are discussed, as well as the biological effects of various cooling systems, and methods for prediction and thermal modelling. Emphasis is placed on the significance of site-specific variations and the necessity for consideration of all alternatives before selection of a cooling system for a particular site.

RÉSUMÉ

Le rapport examine les principes de gestion permettant de protéger les petites étendues d'eau et les petits cours d'eau, profonds ou non, contre les rejets thermiques, et cite des exemples. On définit une petit étendue d'eau comme celle où l'on peut déceler les effets hydrothermiques éloignés d'une décharge dans une grande partie sinon la totalité de la masse. Les effets sur l'environnement du réchauffement d'une petite étendue d'eau naturelle ne se limitent donc pas au voisinage immédiat de la décharge. On classe les petites étendues d'eau en trois catégories: les cours d'eau, les étendues d'eau stratifiées et les non stratifiées. On examine les options de gestion et de protection offertes pour chacun ainsi que les effets biologiques de divers systèmes de refroidissement; on étudie aussi les méthodes de prévision et de construction de modèles de réchauffement. On insiste sur l'importance des variations propres á chaque emplacement et sur la nécessité d'étudier toutes les options afin de choisir un système de refroidissement approprié.

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1. INTRODUCTION

1.1 Small and Large Water Bodies

The rapidly increasing demand for electricity has resulted in a proportional demand to provide water supplies for hydroelectric power and condenser cooling for thermal plants. Up to this point, the thinking that has prevailed regarding the siting of thermal power plants in much of Canada has been that the new plants should use once-through cooling systems and be located, wherever possible, on "large" water bodies. These bodies are considered large if dissipation of the waste heat does not produce a noticeable effect on the environment of the whole water body. In water bodies such as the Great Lakes and the oceans, areas subjected to near field and far field effects of the thermal plume can be distinguished from other areas clearly not influenced by hydrothermal modification. As a result of studies suggesting that the environmental impact of a thermal discharge is quite dependent on the design of the discharge structure, and that impingement and entrainment of aquatic species must be minimized, recent projects have considered, for example, submerged and tunnelled intakes and outfalls which are expensive solutions to the disposal of heated discharge. These aspects were extensively reported in a recent study for Fisheries and Environment Canada entitled "Heated Discharge Management and Control Alternatives for Once-Through Cooling Systems in Large Water Bodies" (James F. MacLaren Limited, 1975). This study also indicated that the main issue in the management of heated discharge from future thermal electric stations is the consideration of all possible alternatives, beginning at the preliminary site selection stage.

The use of small water bodies, either man-made or natural, and rivers can also be considered as cooling options. In some provinces this is the only available alternative for steam-electric cooling. The United States Environmental Protection Agency has proposed amendments to effluent guidelines (U.S. Fed. Reg., 1976) to consider recent man-made ponds and cooling reservoirs to be an environmentally preferable solution in some cases. These "small" bodies can be defined as those in which the far field hydrothermal effects of a heated discharge can be detected in virtually all of the water body. Biological changes produced by the thermal plant are not limited to the immediate area of the outfall and, although not necessarily, may be reflected in a major portion of the water body.

The possible use of these small water bodies is important in Canada simply because the oceans are too far from many large urban load centres and some provinces have no other large water bodies, such as the Great Lakes, to turn to for cooling water supplies. Costs associated with transmitting fuel and electricity to and from a large water body site may be of such magnitude that a smaller water body would be a viable alternative to be considered. Furthermore, even large bodies such as the Great Lakes can have local environmental constraints or sensitive shoreland areas, and thus, it would be necessary to compare these sites with other inland sources. It is also possible to consider some of these alternatives in conjunction with beneficial uses of heating reservoirs, or using a reservoir for the joint purposes of hydroelectrical and thermal generation.

The controlled management of heated discharges to some lakes or rivers with a warm water environment can be considered beneficial, rather than detrimental. The addition of a quantity of waste heat to an environment already unsuitable for certain fish is not necessarily a disadvantage if the lake then becomes eminently more suited for a warm-water fishery, for a waterfowl habitat or for recreation. Reservoirs can also be designed or constructed for multiple purposes, including the use of thermal discharges to keep hydroelectric penstocks clear of ice.

The problem of stimulating a small part of the environment so that it acquires more "southern characteristics", producing an aquatic environment that would be warmer in winter and within which annual biological productivity would be increased, has not been studied in detail in connection with the need to locate thermal electric generating stations on inland water bodies nearer the population centres. More research is required in connection with waste heat to find the best methods to advantageously exploit natural resources to an optimum extent, rather than despoiling them. "Small" water bodies can be more easily controlled from this viewpoint than can large water bodies. It was, therefore, considered that a review of the present state-of-the-art of heated discharge to small water bodies and rivers was required to complement the previous study, and to give to interested parties the main elements for study.

1.2 Brief Review of Heated Discharge in Canada

A summary of current thermal generation in Canada indicates that small water bodies in certain regions are used for cooling purposes and are the sites of proposed expansion. In other regions, they are not. For instance, in the Atlantic Region, Newfoundland-Labrador uses predominantly hydroelectric power. Thermal electric stations are relatively small and those of any size are located on the ocean. On the other hand, Nova Scotia and Prince Edward Island rely principally upon thermal electric power. Again, the majority of the larger stations are located on the ocean and only one station in Nova Scotia is located on a small inland water body. In New Brunswick, major thermal stations are in coastal locations, such as Point Lepreau and Coleson Cove on the Bay of Fundy. The Grand Lake station in the interior is the only large thermal plant that is not located near the sea. The Atlantic Region has not scheduled any major additional thermal electric stations on lakes, rivers, or other small inland water bodies in the near future.

The James Bay and Churchill Falls developments combine to assure Quebec's continued dependence on hydroelectric power for some time. The only sizeable thermal capacity is supplied by the Gentilly and Tracy plants on the St. Lawrence River, and the only planned immediate expansion is at the Gentilly site. A series of site selection studies are, however, underway for future steam electric expansion along the St. Lawrence River before the year 2000.

Ontario has substantially increased its thermal capacity in recent years and has planned or is constructing several sizeable stations. Most of these, however, are on the Great Lakes. There are several stations in the province on inland rivers but the only major near future inland expansion will be the 1200 MW Atikokan plant at Marmion Lake in Northern Ontario.

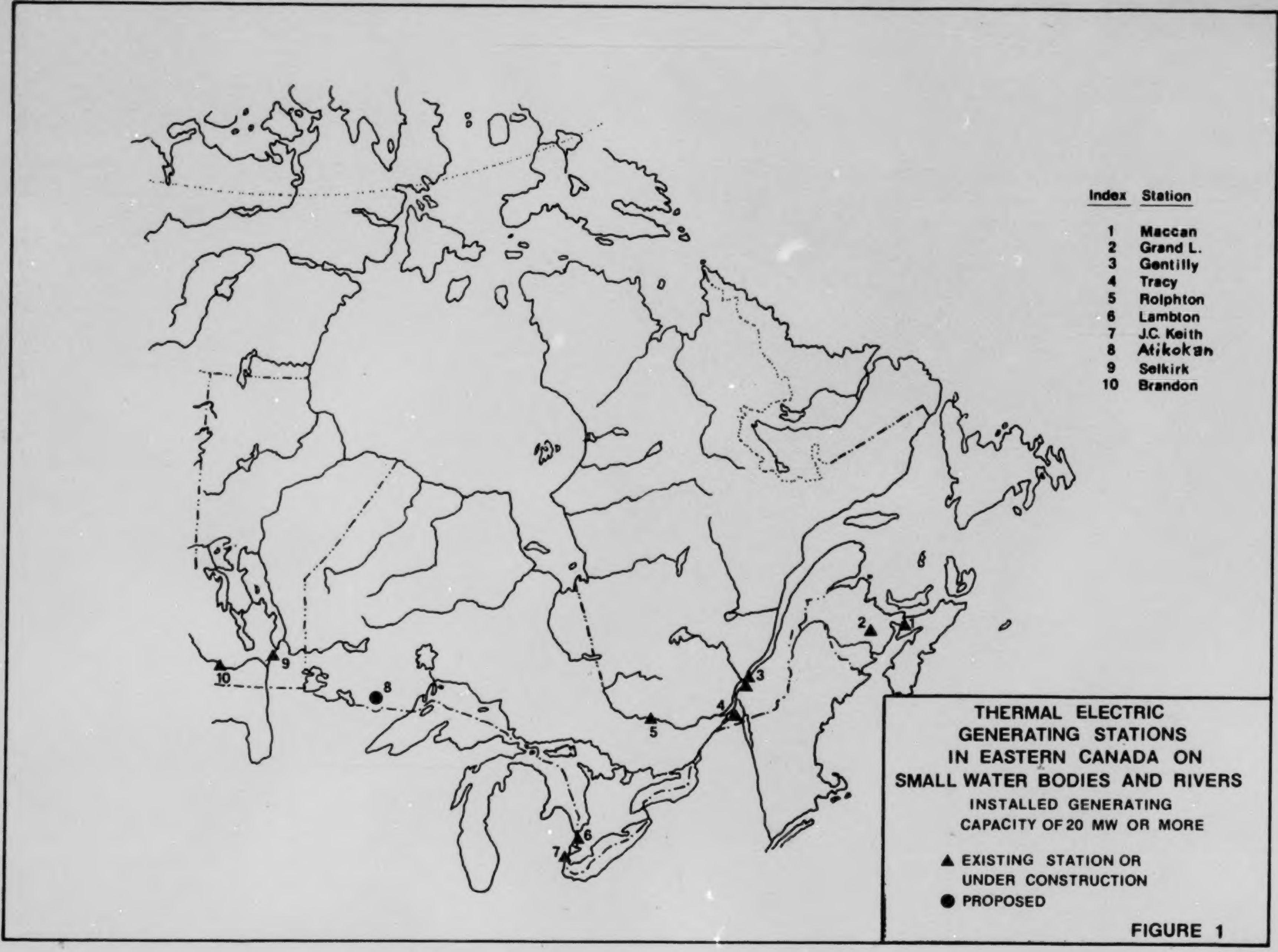
In Western Canada, Alberta and Saskatchewan depend upon thermal power to a large extent, whereas British Columbia and Manitoba have been able to develop more hydroelectric capacity. At present, Manitoba operates two large inland thermal stations at Brandon and Selkirk. Although the province will continue to develop the hydroelectric potential of the Nelson River, Manitoba has embarked on siting and environmental studies for a large thermal nuclear plant for production in the 1980's. Saskatchewan and Alberta are continuing to schedule and construct a number of new thermal plants and are expected to rely almost completely on thermal electric generation in the future (Canada Department of Environment, 1975b). The existing stations are all located on rivers or reservoirs and vary in size up to 975 MW. British Columbia is presently expanding generating capacity by a combination of thermal and hydroelectric generation. Although B.C. Hydro is leaning toward northern hydro developments, thermal stations may be expected to contribute significantly to future energy expansion. For example, a coal-fired station is planned for the Hat Creek area in south-central British Columbia where four 500 MW units are proposed for the mid-1980's. This station may expand in the late 1980's to 4800 MW. The Northwest Territories are expected to continue to build small internal combustion, air-cooled thermal units and small hydro stations for local energy needs. There are presently no plans for large thermal stations in the near future (Canada Department of Environment, 1975a).

Figures 1 and 2 summarize the existing and proposed thermal electric generating stations in Canada on small lakes, reservoirs, and rivers. The figures do not, however, indicate the trend toward increasingly larger facilities. Thermal stations of 100 MW are no longer spectacular by comparison with present typical station sizes of 300 to 600 MW. Both fossil and nuclear stations of the order of 1000 to 4000 MW size composed of 750 or 1200 MW units are proposed for the near future.

This trend, accompanied by a corresponding increase in the demand for condenser cooling water, as mentioned earlier, has resulted in the use of once-through cooling alternatives at sites located on large water bodies and is leading to recirculating systems such as cooling towers and ponds at those sites adjacent to small water bodies and rivers.

1.3 Scope and Report Outline

The selection of a condenser cooling mode most often enters the project planning phase as soon as the need for power is recognized and before sites are being environmentally evaluated. There is a need to



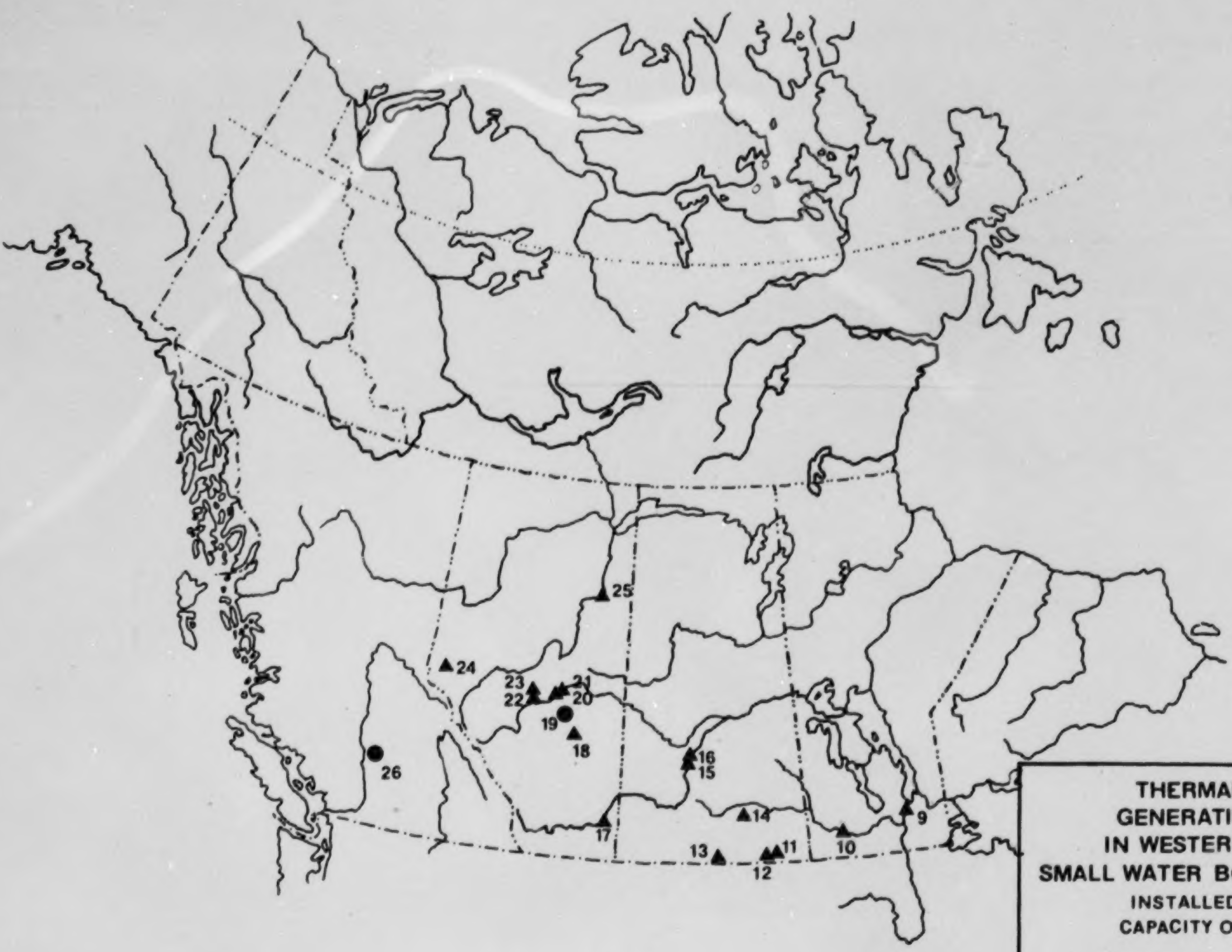
Index	Station
1	Maccan
2	Grand L.
3	Gentilly
4	Tracy
5	Rolphton
6	Lambton
7	J.C. Keith
8	Atikokan
9	Selkirk
10	Brandon

THERMAL ELECTRIC GENERATING STATIONS IN EASTERN CANADA ON SMALL WATER BODIES AND RIVERS

INSTALLED GENERATING CAPACITY OF 20 MW OR MORE

▲ EXISTING STATION OR UNDER CONSTRUCTION
● PROPOSED

FIGURE 1



Index	Station
9	Selkirk
10	Brandon
11	Estevan
12	Boundary Dam
13	Poplar Ras.
14	Regina
15	Queen Eliz.
16	AL Cole
17	Medicine Hat
18	Battle R.
19	Camrose
20	Rossdale
21	Clover Bar
22	Sundance
23	Wabamun
24	H.R. Milner
25	Tar Isl.
26	Hat Crk.

THERMAL ELECTRIC GENERATING STATIONS IN WESTERN CANADA ON SMALL WATER BODIES AND RIVERS

INSTALLED GENERATING CAPACITY OF 20 MW OR MORE

▲ EXISTING STATION OR UNDER CONSTRUCTION

● PROPOSED

FIGURE 2

incorporate environmental considerations from the first planning to the design stages. This may avoid, for example, a decision to use a recirculating mode such as an offstream cooling pond without a dialogue with the environmental agencies, or the selection of an existing water body for cooling purposes based on vague rules-of-thumb indicating requirements such as "1 acre/MW".

After a review of basic concepts, three sections of this report discuss the approaches and methods available for waste heat management on shallow and deep small water bodies and on rivers using examples. These three sections review:

- management alternatives;
- biological effects of cooling modes; and,
- methods for prediction and thermal modelling.

Following these sections, expanded sections are included on a discussion of an approach to cooling system selection.

An objective of this report was also to illustrate that, while very sophisticated models are available for detailed analysis, simple computations can be applied in the initial screening of management alternatives to give much better appreciation of the many interacting variables involved in both man-made and natural water bodies, with and without biological temperature restrictions. Different types of computations and data to be used in this screening process for shallow and deep lakes and for rivers are summarized. Several appendices are included, one of which presents a detailed model for use in the study of shallow water bodies, which was selected after testing and analysis of the models available. As in the previous study it is hoped that this report, which is not intended as a comprehensive manual, will stimulate discussion between experts on the subject of waste heat management in Canada, point out the problems of arbitrary cooling system selection, and emphasize the need for siting studies that are tailored on a case-by-case basis. Only by considering all alternatives at each site can we ensure that the most suitable combination will be determined from an environmental standpoint.

2. REVIEW OF SOME GENERAL CONCEPTS AND REGULATIONS

2.1 General

The amount of heat discharged from steam electric power plant cooling systems varies according to the type of power plant and the efficiency of power production.

New fossil fuel plants have an overall energy conversion efficiency of about 40%. This means that 60% of the input energy is rejected as waste heat. This 60% is comprised of 45% heat removed by cooling water and 15% lost via the stack. In Canada, nuclear plants are about 30% efficient. The 70% of the energy input rejected as waste heat is made up of about 5% miscellaneous losses and 65% removal in the condensers.

The ultimate heat sink for all forms of this energy dissipation is through the earth's atmosphere to outer space. When waste heat carried by condenser cooling water is discharged directly into a water body, heat transfer to the atmosphere occurs over relatively large areas by evaporation, radiation, convection, and conduction.

2.2 Cooling Systems

Condenser cooling water systems are termed "once-through" when the cooling water flow passes through the cooling system only once. The waste heat is discharged into a natural water body such as a lake or river. The once-through system is presently used at almost all large steam electric stations on small water bodies in Canada.

Systems are termed "closed-cycle" when the cooling water is continuously recirculated. The cooling water passes through the condensers and the waste heat is rejected to the atmosphere in cooling ponds, spray ponds, or wet or dry cooling towers. The cooling flow is then returned to the plant for another cycle. Closed systems have not traditionally been used in Canada and presently are only used at two large plants (the H.R. Milner Station and the Sundance Station in Alberta). They are, however, in widespread use in the United States and Europe where once-through systems may be limited by environmental constraints or the lack of an adequate water supply.

Supplemental cooling systems may also be used. In certain cases, a cooling pond or cooling tower is combined with a once-through system to discharge a portion of the total waste heat to the atmosphere before the remainder is discharged to a water body.

2.2.1 Once-through cooling systems

The major components of a once-through cooling system are: the intake structure, the intake canal or tunnel, cooling water pumps, condenser, discharge canal or tunnel, and discharge structure. The basic flow diagram for a thermal generating plant with once-through cooling is shown in Figure 3.

The present state-of-the-art in the design of once-through systems gives the designer the means to analyse and eventually control the magnitude, extent, and distribution of thermal effects in the receiving water bodies. Through design of the intake-outfall structures, there is a certain degree of flexibility in tailoring the temperature distribution in comparatively large receiving waters to minimize the biological impact. By combining good engineering design with proper assessment of biological effects, once-through cooling can remain a viable mechanism for heat dissipation in major rivers, reservoirs and lakes. Also an advantage of once-through cooling is the low consumptive use of water, and the savings in fuel and station energy consumption.

Heat dissipation from the receiving water surface will ultimately return the water to its natural temperature state within a certain distance from the point of heat addition. This distance depends in part on the amount of mixing or dilution between the heated condenser water discharge and the receiving water. At opposite ends of design capability are complete stratification and complete mixing of the heated effluent. In the former case, mixing is avoided and the heated water is "floated" by a low velocity surface discharge onto the receiving water in a relatively thin surface layer. Heat dissipation to the atmosphere is at a maximum rate, and there are no temperature changes at or near the bottom of the receiving water.

It is also possible to completely mix the heated discharge with an available flow past the site. The condenser cooling water is conducted through a diffuser pipe or tunnel and discharged through nozzles or

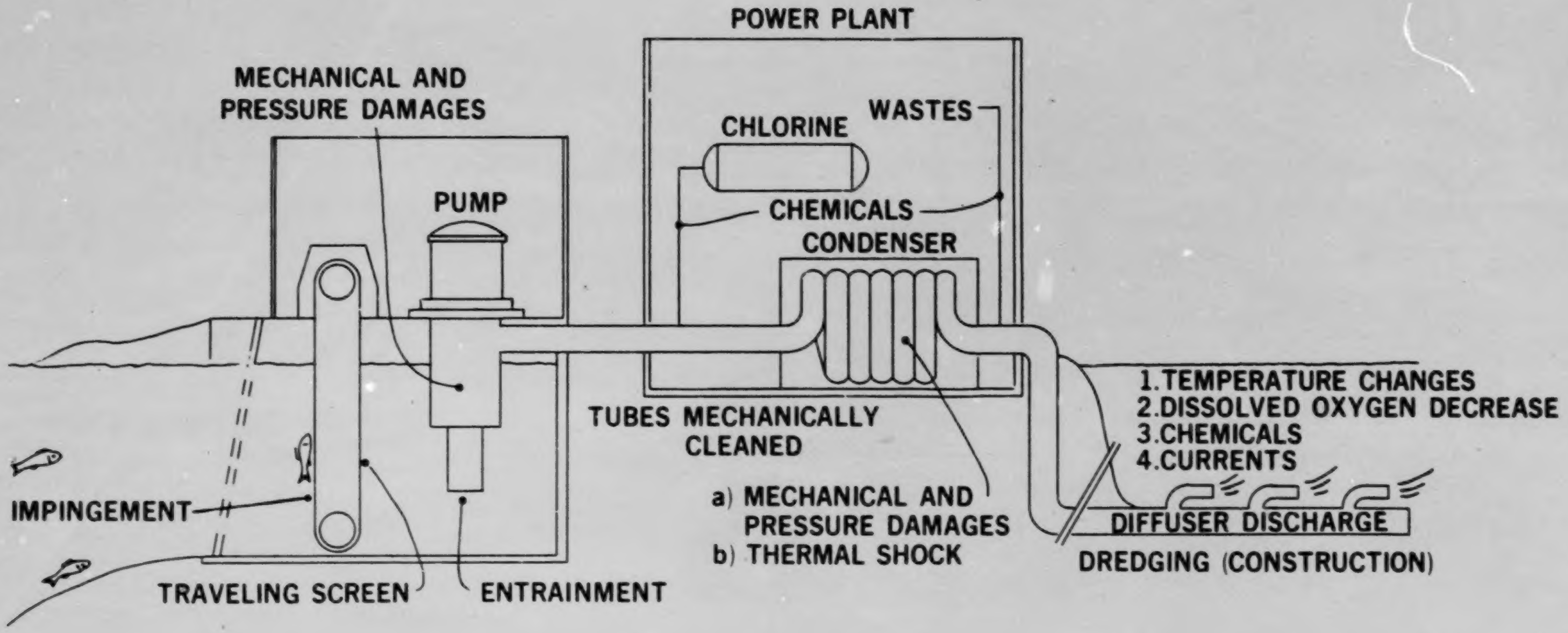


FIGURE 3. ONCE-THROUGH COOLING SYSTEM

ports near the bottom of the waterway. Entrainment of surrounding water into the high-velocity jets produces a rapid dilution. This type of discharge device provides the most rapid temperature reduction within the smallest area. On the other hand, a maximum amount of heat is stored in the water since surface heat dissipation is relatively slow at the very low temperature rises which usually result.

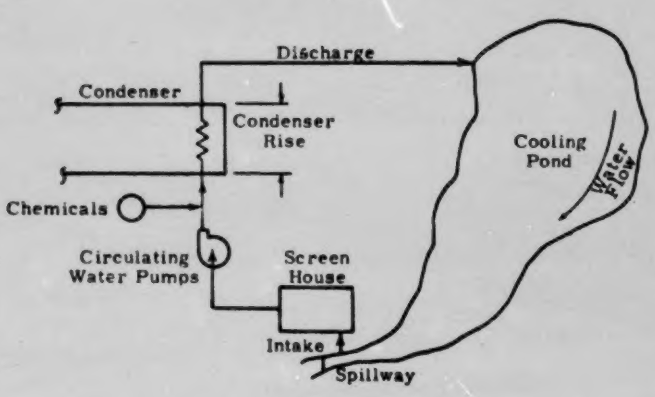
2.2.2 Closed-cycle cooling systems

Recirculating closed-cycle systems are designed to dissipate into the atmosphere almost the entire amount of waste heat carried by condenser cooling water. The heat transfer to atmosphere occurs in cooling towers, cooling ponds, or spray ponds (Figure 4).

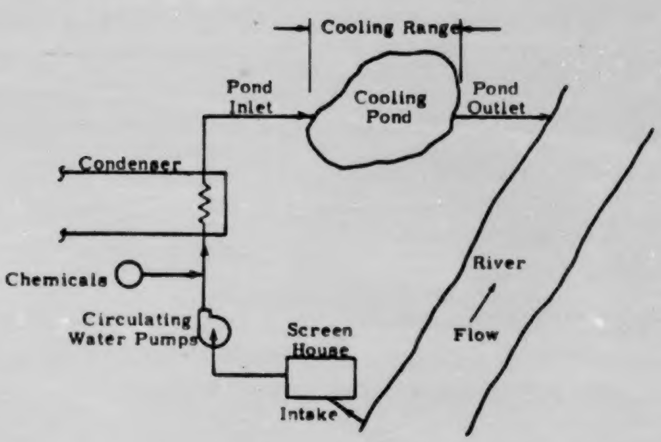
Cooling towers can be of the wet, evaporative type or the dry, nonevaporative type. Depending on the means used for causing air circulation, cooling towers fall into three general categories: those which use fans to force air movement (mechanical draft towers), those which only use wind or natural air currents to move the air (atmospheric towers), and those which have tall stacks to promote the air movement by stack effect (natural draft towers). The large electric utility applications are usually mechanical draft or natural draft towers. Use of atmospheric cooling towers is usually limited to small installations, such as air conditioning, small engine cooling and other comparable heat rejection systems. Limiting factors in the use of wet cooling towers may be (a) consumption of water; (b) restrictions on blowdown discharges; (c) fogging and icing hazards.

The total make-up water requirement for wet cooling towers includes evaporative losses, blowdown, and drift losses.

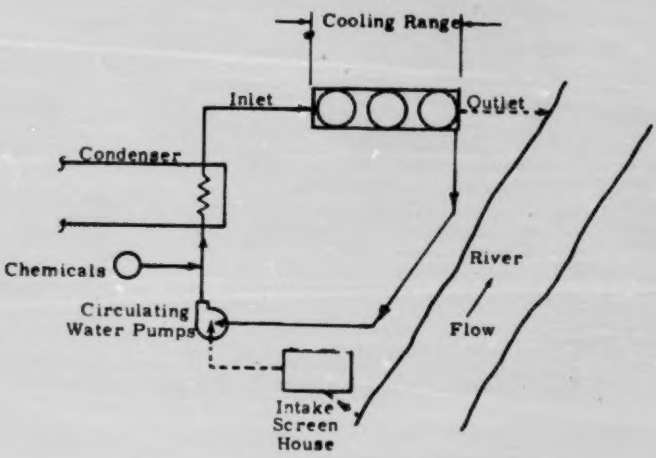
There are two types of dry air cooling systems in general use for power plant cooling. One of these uses an air-cooled stream surface condenser to transfer the heat rejected by the turbine to the cooling air. The other system uses an air-cooled heat exchanger for this purpose. Heat is transferred from the air-cooled condenser, or the air cooled heat exchanger, to the cooling air by convection as sensible heat. The temperature of the dry cooling air, or heat receiver, increases as it passes over the heat transfer surfaces, with the air serving as a heat sink for the process.



(a) CLOSED CYCLE COOLING POND



(b) OPEN CYCLE COOLING POND
(Supplementary)



(c) COOLING TOWERS

FIGURE 4. CLOSED-CYCLE COOLING ALTERNATIVES

The advantage of dry air cooling is primarily that of flexibility in plant siting. The use of dry cooling towers is presently limited to relatively small generating units, but technological progress in this field is anticipated. Presently they impose a penalty on thermal efficiency, and their cost is estimated to be three to five times greater than wet cooling towers.

Cooling towers are now used at only one Canadian steam electric station larger than 20 MW. The 150 MW H.R. Milner Station in central-western Alberta uses a mechanical draft, evaporative cooling tower because the flow rate of the Smokey River is insufficient to meet a once-through demand. The only previous Canadian utility to use a cooling tower was Manitoba Hydro at the Brandon Generating Station, where the tower collapsed.

Cooling ponds, as noted previously, are natural evaporative coolers although they are not usually classified with those evaporative cooling systems using controlled means to promote high heat transfer rates, such as spray ponds or cooling towers. Cooling ponds are extensively used in the United States in geographical areas where the availability of large land areas and low humidity provide effective surface cooling. Heat transfer to the atmosphere occurs by evaporation, radiation, and conduction, and their relative magnitude depends on the temperature of the water surface.

Spray systems can be added to cooling ponds to increase the heat dissipation per unit surface area and reduce the pond size. For large installations, the cost of spray ponds is considerably greater than a comparable cooling tower except in those cases where land cost and terrain make site preparation low in cost. Such systems have been used to date only for relatively small generating units. A recent development in spray pond design is the use of a number of floating spray devices arranged in series which, in some circumstances, can be an economical alternative to the more conventional spray pond system. These spray units require a long channel with a minimum width of about 160 ft. As hot water flows down the channel to the condenser circulating pumps, it is successively picked up, sprayed, and thus cooled. With an existing canal or channel and a low cooling requirement, as is occasionally found with an existing power station, the application may be economically attractive. These have been proposed for possible future use at the Wabamun plant in Alberta. Unlike conventional spray ponds, some of the floating spray systems have lower drift and fogging characteristics, obtained by the use of sprays with large drop size.

2.2.3 Supplementary cooling systems

Supplemental cooling systems are flow-through systems that include cooling towers or cooling ponds tied in with the discharge system. They are designed both to discharge condenser cooling water directly to the receiving body and to allow partial heat rejection to the atmosphere through the supplemental cooling facilities, when required. In the former case, the temperature at the point of discharge is essentially the same as at the condenser outlet; in the latter case the temperature is reduced by an amount dependent on the capacity of the supplemental cooling facility and on atmospheric conditions.

In general, atmospheric wet bulb temperatures have wide fluctuations in comparison to natural water temperatures and at times may even exceed them. Since a supplemental or "helper" wet cooling tower can reduce the temperature of the warm water discharge only to within a certain approach to the wet bulb temperature, there are inherent limitations in its cooling performance and in its effectiveness in controlling thermal effects. Similarly, the performance of a supplemental cooling pond has inherent limitations, since it is controlled by the approach to the equilibrium temperature of the water, which may at times exceed the natural temperature of the receiving water body. They are, however, a most attractive alternative when environmental concerns are related to special conditions, and are often used in summer months only (see Figure 4(b)).

2.3 Environmental and Operational Considerations

2.3.1 General climatological considerations

Small water bodies and rivers can be expected to respond differently to thermal inputs because the hydrothermal behaviour of a water body is greatly influenced by the meteorology to which it is exposed. Consequently, the extensive geographical variation in climatological conditions in Canada plays an important role in the selection of a cooling system or mode of discharge to be used at a specific station. For example, the capacity of a water body to dissipate excess heat to the atmosphere is generally reduced in the winter, because of the presence of ice cover at the water surface. The ice inhibits the free movement of heat.

The potential for surface ice formation on water bodies is present almost everywhere in Canada. As expected, the persistence of the ice cover is largely a function of the latitude. The central portions of the Prairie Provinces and northern Ontario and Quebec typically experience surface ice conditions for an average of at least a month longer than those of southern Ontario, southern Quebec and the Maritimes. Therefore, mid-latitude prairie water bodies dispose of excess heat less efficiently during the winter than their more southern counterparts.

In contrast, the dry windy weather experienced on the prairies in the summer is more conducive to heat dissipation than are the more humid conditions in the St. Lawrence lowland, the Maritime Provinces and the Pacific coast.

Despite the abundance of fresh water in Canada, its distribution both spatially and temporally is very nonuniform. Consequently, many areas such as the southern portions of the Prairies have inadequate supplies of water for at least some part of the year. Therefore, in spite of meteorological conditions which are ideal for the dissipation of waste heat, the use of local water resources for this purpose is limited.

The consideration most specific to water quality in Canadian conditions is that of ice cover. In normal winter conditions most small water bodies in Canada are covered by ice which inhibits the reaeration of the waters by oxygen transfer from the atmosphere. In a free surface situation this process usually represents the main source of dissolved oxygen (DO) replacement. The predominant method of DO removal in water bodies is by bacteriological decomposition of organic wastes. In extreme situations, which are more likely to occur in ice-covered water, all the DO can be used in aerobic bacteriological processes (causing most higher life forms to be nonviable), at which stage anaerobic decomposition predominates. Where a significant biomass is present, oxygen is normally produced during daylight by photosynthesis. However, if there is a cover of ice and a layer of snow this source of dissolved oxygen is inhibited because solar radiation is effectively excluded.

The rate at which most bacteriological and chemical reactions proceed is increased with temperature. In the case where the thermal effluents from a generating plant enter a body of water without causing more than localized ice melting, the rates of all oxygen consuming reactions are increased and, consequently, the naturally low DO levels are further decreased. If the volume of thermal discharge is significant in relation to that of the receiving water, ice cover may be removed for some distance from the outfall. In these circumstances, the discharge will improve in-stream DO in the open water reaches by allowing surface reaeration during winter. However, the additional food requirements of aquatic organisms in the warmer waters can be a problem in "food-limited" waters.

Where a thermal effluent remains trapped below a surface layer of ice, the rate of cooling is greatly diminished as compared with a free surface situation. This is because the thermal conductivity of ice is so low that even a thin layer renders rates of surface heat exchange minimal in relation to equivalent free surface heat exchange rates. Thus, thermal effluents can increase the rates of biological and chemical reactions without improving the availability of dissolved oxygen, and at the same time increase average winter water temperatures.

2.3.2 Biological considerations and effect of heat on aquatic organisms

The importance of temperature to aquatic organisms is well known, and the composition of aquatic communities depends largely on the temperature characteristics of their environment. Organisms may respond to changing levels of temperature in three ways. Firstly, at temperature extremes they die, the mortality rate increasing with the temperature extreme. Over a range of moderate temperatures the rates of their various activities, such as movement and growth, will vary, increasing with increasing temperature at least to a certain point before temperatures become lethal. At higher but still nonlethal temperatures, activity may begin to diminish again. It is apparent, therefore, that organisms have upper and lower thermal tolerance limits and optimum temperatures for growth and activity. These also congregate at preferred temperatures in thermal gradients, and have temperature limitations for migration, spawning, and egg incubation. Temperature also affects the physical environment of the aquatic medium (e.g. viscosity, degree of ice cover, and oxygen capacity). Consequently the composition of aquatic communities in a given biotic province depends, largely on temperature characteristics of the environment.

Temperature effects are the result of interaction between the metabolic rate of an organism, which is influenced by temperature, and its ability to fulfill its needs, e.g. find food or take up oxygen, in a more or less restrictive environment. The optimum temperature, therefore, cannot be predicted from a knowledge of ambient temperatures alone and must be conservatively estimated by assessing the probable effects of an increase in the ambient temperature on a given species.

Secondly, since each different species has its own thermal optimum the balance of interactions between competitors will shift, favouring those species which are more tolerant at the new temperature. As a result, there may be replacement of a desirable species by its competitor, a less desirable species. Thirdly, mobile organisms ordinarily react to the temperature of their surroundings in such a way that they avoid some temperatures and congregate at others.

2.3.2.1 Thermal plumes. The significance of the influence of the thermal plume on the environment depends partly on the size of the plume and partly on the temperature increments it produces, but mostly on its location with respect to biological communities. The effects of the heated water are considered to be more serious if an important biological resource is diminished. Fish species which have commerical or sport value probably receive more attention than other species since, in general, these are the ones that the public values. However, species can also be important from the ecological aspect for normal community function and maintenance.

2.3.2.2 Responses of fish to thermal plumes. The most conspicuous influence of the thermal plume on fish is that it attracts or repels them through their thermoregulatory behaviour. It has been observed in many instances that, in summer, fish tend to avoid zones where warm and cold water mix but congregate in these areas during the cooler parts of the year. This situation varies somewhat from one species to another depending on the preferred temperature. Carp and many catfish species, for instance, have been known to frequent the discharge area during the entire year, whereas coldwater species such as trout may congregate in winter only. Anglers often take advantage of congregations of game fish in thermal plumes.

The lethal effects of residence in a thermal plume may depend on the sudden absence of the plume because of plant shutdown or a storm, since the lethal temperature of an organism depends in part on its thermal history. Thus, winter residence in a thermal plume or discharge canal to which an organism has been attracted by its thermoregulatory behaviour may acclimate it to warm water. Then, if the plant is shut down or the plume dissipated by a winter storm, a fish, for example, so acclimated may be exposed to a lethally low temperature (Alabaster, 1969; Merriman, 1970).

Unless confined by some restriction such as the bounds of a long discharge canal, fish seem to swim freely in and out of a thermal plume and any concentration of a species in the plume would be the result of differential residence time rather than absolute confinement (Neill, 1974). Such wandering, together with fluctuations in the plume related to changes in plume position due to winds and currents, act to prevent permanent entrapment of particular individuals. It is because of such circumstances that the importance of the location of the effluent must be stressed. The effect of a shoreline discharge into a lake is vastly different from that of the same discharge into a river, or into a lagoon with a narrow connection with the main body of water. Thermal entrapment may be a direct cause of death for certain sensitive species, such as the alewife, in fresh water in the spring. At that time of the year, Graham (1956) observed alewife mortalities in Lake Ontario caused simply by their entrance into naturally warmed water over shallows.

2.3.2.3 Benthic organisms. Various species of Mollusca as well as smaller invertebrate forms might not normally be subject to entrapment in a thermal plume because of their mobility. There are, however, many sessile forms of benthic invertebrates and those with limited mobility. These along with plants, are at the mercy of the immediate environment and the effects of a thermal plume upon them could be profound. These forms must be thermally tolerant to exist within the vicinity of the plume. With a shoreline discharge, therefore, the benthic biota in a limited region of bottom immediately surrounding the discharge could be expected to be radically changed by a thermal effluent. However, the changes may not be due to thermal effects alone but might also be caused by induced currents or a combination of thermal effects plus induced currents. Fish may be considered as sessile forms at certain stages of their life cycle, e.g. eggs or larvae.

2.3.2.4 Macrophytes. With regard to the attached plants, two possible effects of thermal effluents can cause the normal flora to become a nuisance growth. Plants existing in the vicinity of a warmed effluent may have a longer growing season and, secondly, the breakdown of organisms entrained and killed by the thermal plume might provide a greater supply of nutrients for the plants. In Lake Julian, North Carolina, which acts like a cooling pond, dense growths of filamentous blue-green algae occur at the warm end of the lake. Similarly, at Lake Wabumun, Alberta, the increased water temperatures and ice-free water conditions caused by thermal effluents have resulted in changes in species composition and production of submerged macrophytes. A rapidly spreading weed species *(Elodea canadensis Michx)* has become the dominant species at the thermal outfalls (Gorham, 1975).

2.3.2.5 Insects. Aquatic insects present a special case because the larvae of these insects are usually found in water. At an adult or pre-adult stage most aquatic insects leave the water and adopt a flying life during which they mate and produce their eggs, which are laid in the water to provide the next generation. If the local thermal regime in the water is altered, emergence may be accelerated and such insects may find themselves exposed to the air at an entirely inappropriate time of the year. Whether such losses of adults and the associated reproductive capability of the species is of significance in a given locality is, of course, a matter of local circumstance.

2.3.2.6 Plankton. Since planktonic organisms are by definition weak swimmers, one would not expect any concentration of plankton by thermal attraction. However, zooplankters have definite, although limited, powers of locomotion and many take part in extensive vertical migrations. Consequently, if, for example, cold water is being incorporated from below into the warm plume as it fans out, there may be a daytime concentration, say, of copepods below the plume as the small crustaceans swim downward against the relatively gentle upwelling to avoid brighter light above. With regard to phytoplankton, there has been the opinion that residence in the thermal plume might lead to enhanced growth and reproduction.

Thermal plumes have received by far the most study during the warm months of the year when the effluent quickly rises to the surface and spreads over it until dissipated. At temperatures below 10^{o}C, there is little difference in water density with temperature and a miniature thermal bar may contain the plume, which will then occupy less surface but will cover more bottom. At temperatures below 4^{o}C the plume can sink in fresh water. The behaviour of the thermal plume in winter may be of special significance under Canadian conditions since some of our important fishes are adapted to very cold water. The lake whitefish, for example, spawns in late fall and its eggs, which are laid on the bottom usually in relatively shallow water, have an optimum temperature for development of only about $1-2^{o}$C (Price, 1940).

2.3.2.7 Gas-bubble disease. When water is heated, the pressure of dissolved gases can be raised above saturation and such supersaturation can induce gas-bubble disease in aquatic animals. Ordinarily, with shallow intakes and discharges on open shores, supersaturation is not a problem. However, if the intake is below the thermocline, more air is dissolved in the water at the lower temperature, compared to epilimnetic, warmer water. Such water discharged at a lesser depth never cools below the prevailing and usually warmer temperature there, and thus adds a permanent and possibly significant excess of dissolved gases to the local water mass. On occasion, such excess of dissolved gases has been observed to produce gas-bubble disease in fish frequenting the plume.

2.3.3 Entrainment and impingement

The major biological impacts caused by the use of water in a once-through cooling mode are entrainment and impingement.

Entrainment refers to the passage of relatively small benthic planktonic and the smaller nektonic forms (egg and larval) through the condenser cooling system. The fraction of these organisms killed is quite variable and such mortality is a subject of considerable ongoing research. Entrainment mortality is not caused by the intake structure itself but by the subsequent condenser cooling water system. The number of organisms that are entrained is generally a function of the intake location.

The effects on aquatic organisms of entering and passing through the cooling water system of a power plant are considered to be more serious than the effects of living in or passing through the thermal plume. This is especially true with respect to fish populations. Small organisms which pass through the condensers may be damaged by thermal shock, mechanical effects such as shear, abrasion and pressure changes, or by chemical additives such as biocides or other chemicals used in the control of water quality or produced by corrosion.

Entrainment may become a serious problem if the number of individuals in a species is reduced by a significant amount and cannot be replaced or compensated for by natural means.

In terms of more planktonic populations, results to date on the whole have indicated that the consequences of entrainment are minor. Entrainment does not appear to significantly effect phytoplankton and zooplankton populations because of the rapidity which which lost individuals can be replaced. This is particularly true if the cooling water requirement is small compared to that of the water source, or when the intake is located in a zone without significant population.

Impingement is the forcing of nektonic species and, in some cases, benthic species against a screen mesh by forces produced by the velocity of water flowing through the screen. In general, the nekton (fish) entrapped in the screenwell will eventually be impinged after becoming exhausted. Mortality can occur because of descaling during escape attempts and from the force of screen wash sprays, by asphyxiation due to closure of the opercula or removal from the water for prolonged periods.

Inadequately designed screens and intakes can lead to the impingement of many nekton. Long intake channels and forebays, in which fish are entrapped in currents, may lead to the exhaustion of fish which otherwise might not be impinged. Any individual which cannot release itself from the screens but is still in a viable condition will be destroyed since, in general, vertical travelling screens backwash the organisms into a trash sump. Designs which incorporate large access canals and require high water velocities through the screens without providing suitable fish bypass facilities and collection areas are to be avoided.

2.4 Operational Considerations

2.4.1 Chemical considerations

Thermal power plants require boiler feed water of a very high degree of purity. Consequently, most plants use a sophisticated water treatment system for boiler make up systems. Typically, this treatment involves the removal of dissolved calcium and magnesium solids ("hardness"), filtration and demineralization. The lime slurry produced in the initial phase is usually disposed of on land in dry beds, while the accumulated solids in the filter (backwash) are often discharged directly to the receiving water. Acids and alkalis used in demineralization are neutralized and eventually returned to the receiving water either directly or by infiltration into the groundwater from storage areas. From time to time, it is necessary to blow down a portion of the water in the boilers. This may be carried out to control the level of water in the boiler as it expands during startup or to limit the buildup of dissolved and suspended solids in the boiler water. Dissolved and suspended solids may enter the boiler water through leaks in the condensers, which would permit cooling waters to enter the condensate. In addition, high purity chemicals are often injected directly into the steam drums to control corrosion, pH and hardness. Thus, these chemicals will all be present in the boiler blowdown water. Typical boiler water constituent concentrations from the Brandon Generating Station, Manitoba, are shown below (James F. MacLaren Ltd., 1976):

Typical Boiler Water Analysis, Units 1-4

Hydroxide alkalinity	30-40 ppm as $CaCO_3$
Phosphates	25-35 ppm as PO_4

Chlorides	20 ppm max. as Cl
Sulphate	300-500 ppm as SO_4 Max.
Sulphite	30-50 ppm as SO_3 max.
Total dissolved solids	1,000 ppm max.
Silica	10 ppm max. as SiO_2
Turbidity	15 ppm max. as SiO_2
Hydrazine	0.2 ppm max. as N_2H_4

2.4.2 Once-through systems

It is desirable to minimize the accumulation of any material on the heat exchange surfaces in the condenser because this reduces the overall heat transfer coefficient for the unit and, consequently, results in a loss of efficiency. Severe accumulations and growths of aquatic organisms in the cooling system increase drag and friction losses and lead to higher pumping costs. Chlorine, as a biocide, is often introduced at the intake in once-through cooling systems to control fouling growth. Some plants use intermittent dosing with relatively high levels of residual chlorine of 0.1 to 5.0 ppm. Others use a continuous low level dosage at 0.2 to 0.5 ppm (Miller and Beck, 1975). Following discharge to the receiving water, the residual chlorine may combined with other pollutants to form various organic-chlorine compounds, depending on the range of compounds in the waters.

In general, there is no problem with the gradual accumulation of trace impurities and dissolved solids in once-through systems. However, in situations where appreciable recirculation (to the intake) occurs, the buildup of undesirable compounds in the receiving water is possible.

2.4.3. Closed-cycle cooling systems

The concentration of dissolved solids in a closed-cycle evaporative system, such as various types of cooling ponds and evaporative (wet) cooling towers, is increased during operation by the evaporative process itself and by those chemicals that are added to control fouling. It is necessary to limit these accumulations to avoid the formation of scale in the condenser and piping works by discharging, either continuously or intermittently, some fraction of the circulating water as blowdown. For fresh water cooling towers, the blowdown volume depends on the rate of evaporative loss of water, the maximum acceptable mineral concentration and the make-up water quality. Typically, the blowdown represents 0.1% - 0.3% of the circulating water rate. Prior to discharge to the receiving water, the hot polluted blowdown is normally treated to avoid adverse environmental effects.

A related phenomenon associated with spray ponds and wet towers, is known as "drift". This is the airborne transport of droplets containing dissolved solids (salts) from the cooling facility and the subsequent deposition of these salts in the environs of the plant. Small droplets, less than 1000 microns in diameter in the case of spray ponds (Guyer and Golay, 1975), are entrained in the rising air flow and exhausted to the environment where local meteorological conditions determine the extent of their transport. Traditionally, cooling tower specifications have called for a drift level not to exceed 0.2% of the water circulating rate (Holmberg and Kinney, 1973). However, more recent investigations such as those carried out for the Chalk Point Power Plant near Washington, D.C. indicate that towers using brackish water may achieve drift rates of no greater than 0.002% of the circulating water rate (Pell, 1975).

Schrecker et al (1975) have suggested that blowdown may be discharged directly to the atmosphere via spray nozzles in cooling tower exhaust air flows if atmospheric transport mechanisms provide dispersal over a large geographic area. If acceptable environmentally, this mode of blowdown dispersal would eliminate the thermal and chemical problems caused by discharge to receiving waters, with a minimum terrestrial impact.

One of the major problems arising from the proliferation of thermal generating stations is the discharge of chemicals into water bodies used as a source of cooling water. More exactly, the problem is not one of the effect of chemicals on the aquatic ecosystem alone, but the combination of thermal and chemical effects. Before the complex interaction of heat plus chemicals on the biota can be appreciated, the effects of individual chemicals on individual organisms must be understood.

The problem facing the operator of a thermal electric generating plant is to maintain those chemicals appearing at the plant discharge at safe levels for aquatic life. The effects of the various chemicals employed in normal power plant operations on aquatic organisms has been discussed in several complete studies referenced at the end of this report.

2.5 Regulatory Considerations

The position of provincial and federal regulatory agencies also plays an important, and sometimes overriding, role in the selection of a cooling system or management alternative for a particular station. Although the purpose of this section is not to outline the historical development of regulatory policies for the disposal of waste heat, it may be necessary to intermix some background of development and some comments with the various criteria or objectives as they are presented.

2.5.1 United States

The strong regulatory position and rapid evolution of policy in the United States has initiated considerable controversy and conflict between regulatory agencies and electric utilities. Thus evolution was summarized earlier (James F. MacLaren Ltd., 1975).

The Federal Water Pollution Control Act, 1956, was amended in 1965 as the Water Quality Act. This Act required development of State standards which, when adopted, differed from state to state in the temperature limits and approach to their definition. In 1967, the first National Technical Advisory Committee on Water Quality Criteria (NTAC) was formed to develop criteria for general areas of water use and collect all water quality criteria into one volume. The Committee recognized that regional variations in climate, topography, hydrology, and other factors must be considered in applying the criteria presented in their 1968 report (U.S. NTAC, 1968).

These "Water Quality Criteria", used by the EPA in evaluating State standards, made recommendations on the maximum permissible temperature rise above ambient conditions and also specified maximum allowable temperature for certain species of fish.

To maintain a "well-rounded" population of both warm and cold water fish, the NTAC recommended maintenance of the range of normal daily and seasonal temperature fluctuations that existed before the addition of heat due to other than natural causes. They also recommended certain maximum temperatures that were not to be exceeded for several species of fish.

To maintain warm water fish, it was recommended that during any month of the year, heat should not be added to a stream in excess of the amount that will raise the temperature of the water (at the expected minimum daily flow for that month) more than 5°F (2.8°C). In lakes and reservoirs, the temperatures of the epilimnion, in those areas where important organisms are most likely to be adversely affected, should not be raised more that 3°F (1.7°C) above that which existed before the addition of heat of artificial origin. The increase should be based on the monthly average of the maximum daily temperature. Unless a special study shows that a discharge of a heated effluent into the hypolimnion or pumping water from the hypolimnion (for discharging back into the same water body) will be desirable, such practice is not recommended.

To maintain trout and salmon (cold waters), inland trout streams, lead waters of salmon streams, trout and salmon lakes and reservoirs, and the hypolimnion of lakes and reservoirs containing salmonids should not be warmed. No heating effluent should be discharged in the vicinity of spawning areas. For other types and reaches of cold-water streams, reservoirs, and lakes during any month of the year, heat should not be added to a stream in excess of the amount that will raise the temperature of the water more than 5°F (2.8°C) (based on the minimum expected flow for that month). In lakes and reservoirs, the temperature of the epilimnion should not be raised more than 3°F (1.7°C) by the addition of heat of artificial origin.

The NTAC report also discussed "mixing areas" as to their effect on the "zone of passage" or movement of aquatic biota. It was recommended that mixing of a thermal discharge with the receiving body should take place as quickly as possible in the smallest possible area. Specific criteria were not advanced as to the size of this area. The maintenance of a "zone of passage" unaffected by these areas of mixing did, however, indirectly define the area. It was recommended that the zone of passage be a continuous stretch borded by the same bank for a considerable distance, and that the passageway should contain preferably 75 percent of the cross-sectional area and/or volume of flow in the stream, reservoir, or lake.

A brief summary of the individual state criteria which evolved at this time is shown in Table 1. Some of the temperature standards are evidently arbitrary and many are closely related to the NTAC criteria. All consider only the effects of the thermal plume and neglect entrainment or impingement.

In 1971, the EPA commissioned the U.S. National Academy of Sciences - National Academy of Engineering (NAS-NAE) to revise and update the 1968 NTAC report and completely re-examine the problem. Their findings were publised as "Water Quality Criteria 1972" (U.S. NAS-NAE, 1972).

The thermal criteria replaced permissible temperature rises with physiologically based requirements and these were radically different from the earlier NTAC criteria. The new criteria were developed based on extensive studies of basic responses of aquatic organisms determined by many biologists, including Canadian scientists Drs. Brett, Fry and Sprague. Permissible limits were not advanced as it was recognized that the requirements must be closely related to each particular body of water and to its particular community of organisms. Instead, methods and procedures were presented for judging thermal requirements; specific numerical values were only advanced for time-temperature relationships and lethal temperatures of some aquatic organisms. It was assumed that the States would select appropriate thermal limits that would protect the organisms. Heat could presumably be added until these thermal limits were reached.

Predicted responses of aquatic organisms should be considered separately for long-term and short-term exposures. Long-term exposures are produced by overall temperature changes in the receiving water body. Short-term exposures are produced by changes due to natural causes, by a short-term change in average temperature, or by the passage of entrained organisms through the cooling system and the thermal plume.

The criteria recommended a method for obtaining maximum allowable temperature for prolonged exposure during warm water months. To maintain growth of aquatic organisms at necessary levels, the criteria suggested that the maximum weekly average temperature should not exceed

TABLE 1. STATE WATER LAWS - SIMPLIFIED SUMMARY OF TEMPERATURE CRITERIA FOR FISH AND WILDLIFE PROPAGATION IN SMALL WATER BODIES AND RIVERS.

	WARM WATER FISHERY		COLD WATER FISHERY				
STATE	MAXIMUM N ALLOWABLE AMBIENT (°C)	MAXIMUM ALLOWABLE CHANGE (°C)	MAXIMUM ALLOWABLE AMBIENT (°C)	MAXIMUM ALLOWABLE CHANGE (°C)	MAXIMUM ALLOWABLE RATE OF CHANGE (°C/hr)	MIXING ZONE ALLOWANCE	REMARKS
ALABAMA	33.9	5.6	33.9	5.6		✓	
ALASKA	15.6	10% of ambient	15.6	10% of ambient	0.3		
ARIZONA	33.9	2.8	12.8-21.1(SWMW)	7.1			
CALIFORNIA	-	2.8		prohibited			some specific body criteria
COLORADO	32.2	2.8	21.1	1.1		✓	no discharge to hypolimnion 3°F to epilimnion
CONNECTICUT	29.4	2.2	29.4	2.2		✓	
DELAWARE	29.4-30.6	2.8	29.4-30.6	2.8		✓	basin by basin specific
D.C.	32.2	2.8	32.2	2.8	gradual	✓	
FLORIDA	site specific		site specific			✓	
GEORGIA	34	5.6		prohibited		✓	no change in trout waters
HAWAII		0.8		0.8		✓	some specific body criteria
IDAHO	20	1.1	20	1.1		✓	" " " "
ILLINOIS	32.2	2.8	15.6	2.8		✓	" " river " no disch. to hypolimnion
INDIANA	site specific	2.8	18.3	2.8			
IOWA	32.2	2.8,1.7 lakes	20	2.8	1.1	✓	
KANSAS	32.2	2.8,1.7 epilim	32.2	2.8,1.7 epilim		✓	
KENTUCKY	31.7	2.8,1.7 epilim	31.7	2.8,1.7 epilim		✓	max. allow varies thru year
LOUISIANA	36	3	36	3			some specific river criteria
MAINE	28.9	2.8,1.7 epilim	20	2.8,1.7 epilim		✓	
MARYLAND	33.9		22.2			✓	rise a function of ambient
MASSACHUSETTS	28.3	2.2	20	2.2		✓	
MICHIGAN	32.2	5.6	21.1	5.6		✓	
MINNESOTA	32.2		30			✓	
MISSISSIPPI	33.9	5.6	33.9	5.6		✓	
MISSOURI	32.2	2.8		1.1			no increase to lakes, reservoirs
MONTANA		1.1-2.2		1.1-2.2			
NEBRASKA	32.2	2.8-5.6	18.3	2.8	1.1		
NEVADA	20-30		14				
N.HAMPSHIRE	[WTAC]	2.8,1.7 epilim	[WTAC]	2.8-1.7		✓	[WTAC]
NEW JERSEY	30	2.8,1.7 epilim	20	1.1		✓	
NEW MEXICO	33.9	2.8	21.1	1.1		✓	other criteria for specific rivers
NEW YORK	26.7	2.8	20	1.1		✓	
N.CAROLINA	28.9	2.8	20-21.1	1.7		✓	
N. DAKOTA	32.2	2.8	32.2	2.8		✓	other criteria for specific rivers
OHIO	33.9		22.8			✓	
OKLAHOMA	23.9-33.9	2.8	21.1	2.8		✓	other specific lake & river criteria
OREGON			17.8	1.1			
PENNSYLVANIA	30.6	2.8	14.4	2.8	1.1		other criteria for specific rivers
RHODE ISL.	28.3	2.2	20	2.2		✓	
S.CAROLINA	32.2	2.8,1.7 lakes	28.9	2.8,1.7 lakes		✓	
S. DAKOTA	29.4	2.2	20	2.2		✓	
TENNESSEE	20	3	20	3	2.0	✓	
TEXAS	35.6	2.8	35.6	2.8		✓	other criteria for specific rivers
UTAH	26.7	2.2	20	1.1			
VERMONT		0.6-2.8		0.6		✓	no hypolim. withdrawal
VIRGINIA	32.2	2.8,1.7 epilim	21.1	2.8,1.7 epilim		✓	" " "
WASHINGTON	site specific		site specific				
WISCONSIN	28.9	2.8	no adverse change		1.1	✓	
W. VIRGINIA				2.8,1.7 epilim			basin specific criteria
WYOMING		2.2		1.1		✓	

one-third of the range between the optimum temperature and the ultimate upper incipient lethal temperature of the species. Thus the maximum acceptable temperature is the:

$$\text{optimum temp.} + \frac{\text{ultimate incipient lethal temperature} - \text{optimum temperature}}{3}$$

The extreme temperature above the weekly average should not exceed the criterion for short-term exposures.

Prolonged exposure to temperature during the winter months can preclude safe return of an organism to ambient or even optimum temperatures. The criteria recommended that "important species should be protected if the maximum weekly average temperature during winter months in any area to which they have access does not exceed the acclimation temperature (minus a $2^{\circ}C$ safety factor) that raises the lower lethal threshold temperature of such species above the normal ambient water temperatures". The discussion suggests that areas of maximum temperatures, such as discharge canals, should not be accessible to important aquatic life for sufficient time to allow thermal acclimation.

Finally, during reproduction seasons, temperatures should meet specific requirements for successful migration, spawning, egg incubation, fry rearing, and other important functions of the species. This includes preservation of normal species diversity and prevention of undesirable growths of nuisance organisms.

On the other hand, the criteria also consider time dependent maximum temperatures for short-term exposures. The length of time that 50 percent of a population will survive temperatures above the incipient lethal temperature can be calculated from a regression of experimental data as follows:

$$\log(\text{time}) = a + b(\text{temp})$$

where time is expressed in minutes, temperatures in degrees Celsius and a + b are constants characteristic for each species. This resistance time equation may be modified to assure no mortality by incorporating a safety factor (which at that time was suggested to be $2^{\circ}C$), and also to define conditions for survival (right side of equation less than or equal to 1) as follows:

$$1 \geq \frac{\text{time}}{10^{(a + b\,[\text{temp} + 2])}}$$

This recommendation applies to entrained organisms and to organisms passing through a plume mixing zone, defined as the region with boundaries beyond time dependance. Within this region the quality characteristics are different from those of the receiving water. It should be pointed out that this definition is somewhat different from the physical process definition. The criteria also consider the difference in behaviour of strong swimmers, weak swimmers and drifting organisms. Strong swimmers are capable of avoiding the mixing zone, as demonstrated by several field surveys. The drifting organisms can become entrained in the discharge plume and carried through the mixing zone.

Because of varying local, physical and chemical conditions and biological phenomena, case by case studies are considered necessary to determine the assimilative capacity of the system. As a guideline, mixing zones should be minimized by appropriate discharge location and design. The NAS-NAE criteria recommended that "no more than 2/3 of the width of a water-body should be devoted to mixing zones, thus leaving at least 1/3 free as a zone of passage for migrating species". In general, sites should be chosen to avoid major migration routes and/or important spawning areas.

There is evidently a need to combine the knowledge of physical (namely temperature prediction) and biological processes in criteria which may lead to site-tailored standards and focus on the total effects of the cooling water system. The study of available literature and discussions with many specialists in the field indicated that the U.S. NAS-NAE criteria come closest to meeting this requirement. Even these, however, have neglected the mechanical effects of entrainment and impingement.

On the other hand, in late 1969, the U.S. Congress passed the National Environmental Policy Act (NEPA) which required environmental statements on major federal actions. These were to be reviewed by federal, state, and local agencies and the final environmental statements submitted to the Council of Environmental Quality (CEQ). The Atomic Energy Commission (AEC) was required to implement the requirements of NEPA as of January 1970. All licensing actions taken between January 1970 and July 1971, would require an appropriate NEPA review. This latter item had a significant impact on the AEC regulatory program by creating a backlog of work which had to be handled on an expedited basis.

The problem encountered in the task of applying a full NEPA review to plants already in operation, or in various stages of construction, raised a significant number of problems of a legal and technical nature. The AEC tried to meet these requirements by "Regulatory Guidelines for Preparation of Environmental Reports for Nuclear Power Plants" (March 1973, revised in January 1975), and "General Environmental Siting Guidelines for Nuclear Power Plants" (December 1973). NEPA policies for conventional fossil fueled plants (which are not under federal jurisdiction) led to the preparation of environmental impact statements by the U.S. Corps of Army Engineers.

In the meantime, in 1972, Congress adopted a new Federal Water Pollution Control Act which revised some of the provisions of the 1965 Water Quality Act. This act set up goals such as eliminating the discharge of pollutants into navigable water by 1985, providing water quality for recreation in water by 1983, and declared that the discharge of pollutants and waste treatment were national policies. The change in philosophy was that limitations were no longer related to the receiving water body but to the effluent. Section 304(b) of the Act requires that point source discharges of pollutants must achieve, not later than July 1, 1977, effluent limitations based on the best practicable control technology currently available ("BPCTCA") or any more stringent limitation required by certain State or Federal laws or regulations. They must further achieve, not later than July 1, 1983, effluent limitations based on the best available technology economically achievable ("BATEA") (Section 301).

An important section of the Federal Water Pollution Control Act is Section 316(a) which provides:

> "With respect to any point source otherwise subject to the provisions of section 301 or section 306 of this Act, whenever the owner or operator of any such source, after opportunity for public hearing, can demonstrate to the satisfaction of the Administrator (or, if appropriate, the State) that any effluent limitation proposed for the control of the thermal component of any discharge from such source will require effluent limitations more stringent than necessary to assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on the body of water into which the discharge is to be made, the Administrator (or, if appropriate, the State) may impose an effluent limitation under such sections for such plant, with respect to the thermal component of such discharge (taking into account the interaction of such thermal component with other pollutants), that will assure the protection and propagation of a balanced, indigenous population of shellfish, fish, and wildlife in and on that body of water".

The EPA interpreted this policy to mean that heat is a pollutant similar to all others. Direct transfer to the atmosphere by means of recirculating systems, rather than once-through systems was considered the best applicable technology (U.S. Federal Register, 1974). The regulations provided that new sources, or existing sources which did not have a cooling lake in use or under construction by October 4, 1974, may not discharge heat to navigable waters unless such discharge is from cooling towers. New power plants may apply for once-through cooling systems through Section 316(a) of the 1965 Act, which requires a demonstration that an alternative cooling system is equally as good as the suggested cooling modes and will cause no harm to the environment. This continues to be valid.

Section 316(b) of the same Act concerns technical requirements for cooling water intake structures, and requires that "the location, design, construction, and capacity of the cooling water intake structures reflect the best technology available for minimizing adverse environmental impact" (U.S. Federal Register, Dec. 1973). The term "intake structure" means the total structure used to direct water from a water body and, in 316(b) determination, covers the effects from the intake source to the point of heated discharge. Guidelines suggest that the determination with respect to 316(a) should be made in conjunction with the determination required by 316(b).

The difficulty in complying with Section 316 and the associated implementation guidelines is that they are too qualitative and too loosely defined. This has led to legal actions and delays inimical to present energy needs, and may have been avoided by following an approach similar to the NAS-NAE criteria. Although very strongly criticized, the EPA has maintained their position requiring recirculating cooling systems discharging from cooling towers or off-stream cooling ponds.

Very recently, however, the EPA proposed amendments to certain of the final effluent limitations and guidelines (U.S. Federal Register, March 1976). The proposed amendments apparently resulted from almost two years of study by a cooling lake policy working group into the environmental and technological problems with the employment of man-made cooling lakes. The working group indicated that, due primarily to the uniqueness of the steam electric industry and the pollutant being discharged, on-stream man-made recirculating cooling water bodies may be the most environmentally acceptable means of dissipating waste heat at certain sites.

The proposed guidelines impose a three-criteria test to determine whether a man-made lake may be deemed to be the best available technology for new steam stations. Initially, the construction and operation of the impoundment must be environmentally acceptable in terms of effect on aquatic life, wildlife, municipal water supplies and recreation. The EPA believes that the upper reaches of many streams do not represent important biological areas and that the creation of an upstream reservoir may in fact improve the resource and be environmentally preferable. The further downstream the reservoir is located, however, the greater will be the potential for damage to existing stream populations and thus it will be more difficult to satisfy the site-specific environmental criteria.

The remaining criteria are more technical but do assist in limiting the location of the cooling reservoir. The second is a thermal efficiency loss, "requiring that the discharge from the water body, on an ... annual basis, contain no more than 2% of the waste condenser heat passed to the cooling water body". This test requires a heat budget determination and is formulated to ensure that the reservoir acts as a cooling lake.

The third criterion established a "flow distribution limiting the total discharge from the water body .... to no more than 100 cfs per

1000 megawatt generating capacity of the facility". This criterion is advanced to ensure that the reservoir acts as a recirculating body rather than a flow-through body.

There is evidently some disagreement over the establishment of these limits, however (Garson, 1976). The limits are rather arbitrary because they have been based to a large degree on only qualitative assessment of reservoirs presently used for cooling. The 2% limit has been arbitrarily selected because it is too restrictive to be modelled and it is expected that this figure will be increased to a more reasonable limit of about 10% following comments from American utilities. It is also evident that there will be wide variations in the released heat at different times during the year, although the annual limit on total heat released may be achieved.

The 100 cfs release figure was also selected after a qualitative review. On one hand, the EPA Effluent Guidelines Division suggested a 30 cfs/1000 MW release would be all that would be required. On the other hand, the Regional EPA offices suggested 200 cfs/1000 MW would be more in keeping with riparian release requirements and avoid extensive algal blooms.

In a sense, this new proposal also represents a reversal in the EPA position by allowing on-stream cooling. In the context that it does restrict cooling to recirculating systems, however, the EPA policy is being maintained. To date, there has been a very limited response from the American utilities. On one hand, it is expected that the response will be favourable. It does allow employment of another cooling mode that may be less expensive than towers and for station siting inland. The policy is also at least partially site-specific. However, because the two "technical" criteria are evidently arbitrary, it is expected that there will be some further discussion prior to establishment of final requirements.

2.5.2 Some other countries

Several countries outside of North America have also adopted temperature standards or tentative guidelines applicable to waste heat disposal.

In the Soviet Union, regulations covering waste heat discharge have been in existence since 1961. The Code of Water Protection limits the permissible temperature increment of rivers and lakes open to public use to 3°C in summer and 5°C in winter. Once-through river cooling is therefore practically limited to large streams whose flow rate is at least three times larger than the required condenser flow rate. Furthermore, the Code of Water Protection specifies that complete mixing of the heated effluents with the river water must take place within 500 metres from the release point. These protective standards have also been adopted in Poland and the CSSR.

In West Germany, standards are developed by water commissions coordinating the activity in several provinces for a given water body. In general, however, country-wide standards are being applied to once-through, on-stream cooling. The standards indicate that the maximum temperature at the end of the discharge canal must be less than 30°C and 28°C after mixing. The maximum temperature rise in surface water after mixing is limited to 3°C. The use of once-through cooling is not prohibited provided that these criteria are met and environmental monitoring is not required. Brochures for public information show the results of measurements and mathematical modelling comparing measured existing and permissible temperatures along the stream. These presentations indicate the spots with temperature increases above specified limits. Authorization for the siting of new power plants is given on the basis of a report regarding the effects of heated outfalls and chemical discharges.

No national legislation exists in France on the matter of waste heat discharges into water bodies. However, all thermal and nuclear projects must be approved by the Prefectoral Authority of the relevant Department. The investigations are carried out by the Public Works or Waterway Services. There is no preset pattern for determining allowable temperature limits.

In Britain, the Steering Committee on Water Quality of the British Department of the Environment supervises pollution control organizations of the Natural Environment Research Council and the River Basin Council. The control of thermal releases to rivers is still usually negotiated between the Central Electric Generating Board and individual river authorities. On a site-by-site basis, limits are set in terms of temperature of the discharge or in terms of permissible temperature rise in the river after mixing.

In Switzerland, thermal releases from power plants into rivers have been subject to certain temperature limits since 1968. As Switzerland is a region of cold waters (semi-stenothermic conditions), it was recommended that a temperature maximum of 25°C, which is 5°C above average summer conditions, should nowhere be exceeded after mixing. A limit of 30°C is set at the end of the condenser discharge canal. A temperature rise of 3°C (in certain seasons, and under favourable conditions, 5°C) can be permitted in the rivers without violation of the Swiss law on water protection. These temperature limits are applicable only to rivers exhibiting a low pollution level. Where this condition is not fulfilled, once-through river cooling is still possible for the new nuclear plants being planned, even on large rivers (the Rhone excepted).

2.5.3 Canada

The situation in Canada is much different than in the United States because of two related factors. Firstly, the majority of Canadian power has been produced by hydroelectric means, by thermal stations on large bodies of water, or by gas turbine operations. As a result, there are less than 30 relatively large stations discharging waste heat to small water bodies and rivers, which is almost an order of magnitude fewer than the corresponding number in the States. Secondly, Canadian environmental policy was developed several years after that in the States. Most activity dates from the early 1970's when the Federal Department of the Environment was formed and passage of the Canada Water Act provided for Federal-Provincial water quality cooperation. During this period there has been enough time to observe the reasonable approaches to waste heat management which have been advanced elsewhere and to understand that the present state-of-the-art requires a case-tailored approach.

Without delving too deeply into the resource allocations defined under the terms of the British North America Act, it is sufficient to say that natural resource ownership is primarily provincial. The provinces have authority to legislate in the fields of water supply, pollution abatement, and power development. The Federal government may legislate over navigation and fisheries, and interprovincial and international affairs. At the Federal level, legally prescribed limits for heated discharge have not as yet been advanced for cooling systems on small water bodies and rivers. Fisheries and Environment Canada may prepare regulations, principally under the Fisheries Act and the Canada Water Act, respecting the quality of water and the obstruction and pollution of any waters frequented by fish. Thus, both the Federal and Provincial governments are responsible for managing and regulating water resources.

The Inland Waters Directorate of the Department of Fisheries and Environment has published preliminary "Guidelines for Water Quality Objectives and Standards" (1972). Proposed temperature criteria are presented for four levels of protection for an ecosystem or water body:

1. For any water body or portion to be preserved in a pristine state, "no change beyond natural minimum and maximum temperatures" is recommended.
2. To maintain water bodies at a high quality, no change greater than 0.5°C is recommended.
3. "No change greater than 1.0°C beyond natural minimum and maximum temperatures" is recommended for waters receiving wastes to the extent that harmful effects do not occur.
4. "No change greater than 2°C" is recommended for waters used for discharge zones.

In addition to these criteria, it is recommended that "the natural pattern of seasonal and daily temperature fluctuation should be maintained".

The significance of water intake was also recognized in the guidelines and several examples of limiting velocities were presented. It is interesting to note, however, that many of the subsequent provincial water quality objectives ignored the importance of intake problems.

At that time, it was also recognized that a uniform standard could not be applied in a country as large as Canada, and that each area must be managed or planned on its own merits.

Provincial criteria for control and management of heated discharge varies from province to province. In the Maritime region (Newfoundland, Nova Scotia, Prince Edward Island and New Brunswick), there have been no general criteria developed for thermal discharges from steam electric power plants to small water bodies. In most instances, temperature criteria would be dictated by fishery concerns and each proposed station would be assessed on a site-specific basis. As with regulations covering other discharges from the industrial sector, the regulations for thermal discharge from steam-electric stations could specify a mixing zone, a maximum ambient temperature not to be exceeded, or a limitation on the change in temperature. An example of the latter criterion is that specified for two thermal stations in New Brunswick which are limited to a 5°C (9°F) temperature rise at the surface of the ocean. This is a federal criterion which followed site-specific studies of fish migration routes and specific biological conditions in the proximity of the plants.

Regulations in Quebec may be set up to classify waters, define quality standards, and determine modes and temperature of discharges for thermal generation by stations larger than 3 MW under the Environmental Quality Act of 1972. It appears, however, that regulations for the discharge of waste heat and the design of intake and outfall structures have not as yet been advanced for large thermal stations, such as Gentilly. Temperature rise in the large mixing zone varies between 3.5°C and 10°C above the ambient river temperatures.

In Ontario, broad powers to prevent pollution and to control water quality are contained in the Ontario Water Resources Act, the Environmental Protection Act, and the Environmental Assessment Act. These Acts give the Ministry of the Environment the authority to supervise all surface and groundwater in Ontario and to require environmental studies for all major projects.

The Ministry of the Environment outlines temperature criteria in its publication "Guidelines and Criteria for Water Quality Management in Ontario" (1975). These guidelines state that heated discharges to inland waters will not be permitted unless it is clearly demonstrated that heated effluents will not endanger the production and optimum maintenance of wildlife, fish and other aquatic species. Inland trout and salmon streams and lakes, and the hypolimnion of lakes and reservoirs containing salmonids and cold water forms should not be warmed. Heat should also not be discharged in the vicinity of spawning or migrating fish populations and normal and daily season temperature variations should be maintained. In addition, the criteria recommend that water for cooling should not be pumped from the hypolimnion of a lake to be discharged to the same body of water.

Ontario Hydro and the Ministry of the Environment have recently determined that it would not be productive to locate large steam electric stations on small lakes and rivers in southern Ontario, even with auxiliary cooling in recirculating systems. Considering the size of future stations in Ontario (2,000 MW plus), it is generally expected that the Great Lakes will be the site of future expansion if the assimilative capacity can be properly used (Johnson, 1976). The same policy and criteria apply to northern Ontario, with the exception of Snow, Abie and Icy Lakes on the Marmion Lake chain which, as an economic necessity, were recently dedicated as cooling lakes for the proposed Atikokan plant by the Cabinet of Ontario. In this instance, however, the decision was preceded by environmental studies. These are still ongoing to determine an acceptable discharge temperature and outfall alternative.

Objectives for surface water quality have been presented, but are still being modified and developed in the Province of Manitoba. These objectives are being advanced to comply with the Clean Environment Act, the Canada Water Act and the Fisheries Act and are enforced through the Manitoba Department of Mines, Resources and Environmental Management. The waters of Manitoba are presently being grouped into general use categories such as domestic consumption, fisheries and recreation, and industrial consumption. Each group has been subcategorized according to existing or desired quality and categories have been advanced for some of the major rivers in the province.

Heated discharge objectives are considered in the fisheries and recreation categories and apply to areas outside initial areas of mixing. An increase no greater than 0.5°C is allowed in Class 2A waters to "permit the propogation and maintenance of warm or cold water sport or commercial fishes". An increase no greater than 1.0°C is allowed in Class 2B waters so as to "permit the propogation and maintenance of cool or warm water sport or commercial fishes".

An increase no greater than 2.0°C is allowed in Class 2C waters. The quality of this class permits the "propogation and maintenance of rough fish". Maximum daily or monthly temperatures not to be exceeded have been cancelled and effects such as entrapment and entrainment are not considered at this time. The mixing zone for point source discharge may extend up to 300 feet in all directions for lakes, and up to 300 feet downstream for rivers. In both lakes and rivers, the zone can extend from the bed to the surface and must be less than 25% of the width of the receiving body.

Although these objectives have been presented and new objectives will be published during 1976, in practice it appears that each source will be evaluated on a case-by-case basis.

The Saskatchewan Department of the Environment, formed on proclamation of the Environment Act in 1972, is charged with the management and protection of the aquatic environment, principally under the Water Resources Management Act, the Water Rights Act, the Department of the Environment Act and the Pollution of Waters (Prevention) Act.

The 1975 "Surface Water Quality Objectives" for Saskatchewan state that the ambient temperature is "not to be increased by more than 3°C" beyond a zone of initial mixing. The mixing zone is to be defined for each site on an individual basis. A zone of passage must be maintained in the outfall vicinity. The regulations also call for submergence and diffusion of heated discharge, but Environment Saskatchewan can designate any outfall as exempt from this requirement as a result of a demonstration of no environmental effect. To date, the Saskatchewan Department of the Environment has not identified significant problems with heated discharges from the province's thermal electric stations and off-stream cooling is not required.

Recently, the Saskatchewan Department of the Environment has considered siting and environmental studies to be necessary to determine potential impacts of proposed power projects. The Poplar River power project is the first of any size to be examined for potential effects.

All studies are reviewed by a Board of Inquiry under the Department of the Environment Act.

The Alberta Department of the Environment may make regulations prescribing the maximum temperature or the permissible change in temperature of surface waters. The principal legislation for heated discharge control is contained in the Clean Water Act and the Department of the Environment Act.

Alberta surface water quality criteria state that thermal effluent should not be discharged at more than 3°C above the ambient water temperature. Each plant is considered on a site-specific basis and, in the power development industrial sector, an offstream cooling policy is developing. This policy appears to be effective; several proposed power stations will use closed-cycle cooling and one existing station has recently been backfitted with a cooling pond. A comparison of cooling alternatives and environmental impact studies are required for each new site.

The British Columbia Department of Lands, Forests and Water Resources regulates thermal discharge through the Pollution Control Act and the Water Act. Pollution control regulations prescribe standards regarding the quality or character of effluents from all industrial sectors, and heated discharge must be approved by the Pollution Control Board of the Department. The objectives are applicable to all water bodies as specific water body classification has proved impractical.

There are no regulations for discharge from large thermal electric stations on inland water bodies. However, siting and environmental impact studies are required for new stations to enable the Department to determine site specific criteria for the mode of cooling and type of discharge.

The selection of a waste heat management alternative in Canada is thus required to meet certain environmental objectives which, in many cases, are flexible and tend toward site-tailored conditions. The new Point Lepreau station in New Brunswick serves as an example to show that, once the site is selected, the environmental studies and design modifications can be conducted on the basis of a program defined by the environmental agencies. The need for flexibility can be illustrated best by the rapid changes in the state-of-the-art, changes in political and economic conditions, and by changes in siting requirements in countries such as the United States.

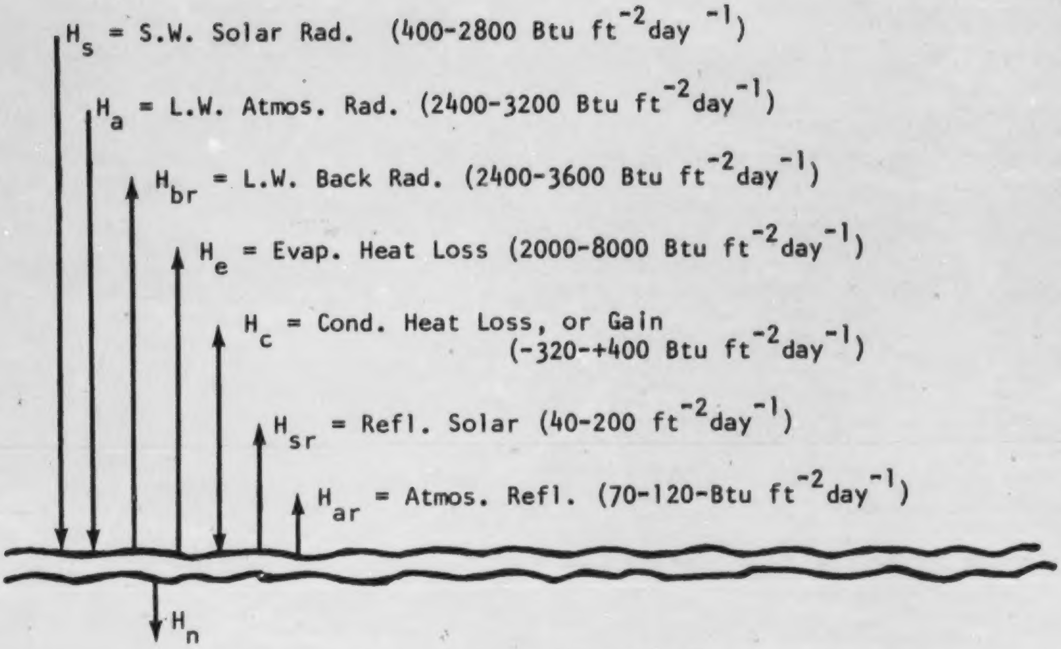
At the same time, there is not yet a general siting and screening procedure available to incorporate environmental studies, or the requirements of environmental legislation. To this purpose, a general approach is advanced in later sections of this report.

2.6 Hydrothermal Considerations

Predictions of temperature changes in water bodies due to heated discharges from power plants are accomplished by means of hydrothermal modelling. Modelling is useful in projecting operational characteristics, such as the potential for recirculation, or determining the size and configuration of a cooling water body for the most efficient and economic cooling. It may also be used to illustrate that environmental criteria, such as temperature restrictions, can be met by a particular alternative or modification to a given design. The hydrothermal models used in these assessments can be simple or complex, i.e., analytical and numerical. The following discussion of the heat balance is included to illustrate that the general process of characterizing the hydrothermal nature of a water body is not a simple one. Additional discussions on evaporation theory, equilibrium temperatures and surface heat exchange have been included in Appendix A and Appendix B.

All the heat added to a body of water as a result of heated cooling water discharges is eventually lost to the atmosphere via the water surface. The shape and size of the water body in conjunction with ambient meteorological conditions determine the extent of the thermal modification caused by the heated discharge

The dissipation of heat from the water surface to the atmosphere takes place through various physical processes which, when expressed ed mathematically, are known as the heat balance (Figure 5). Under natural conditions, the water body receives heat at the surface from solar radiation. In addition, when the water body is used for cooling purposes, heat is added to the water body by the thermal discharge. Heat dissipation at the water surface is comprised of long-wave radiation, conduction to the atmosphere and evaporation (or condensation).


H_s = S.W. Solar Rad. (400-2800 Btu ft^{-2}day^{-1})
H_a = L.W. Atmos. Rad. (2400-3200 Btu ft^{-2}day^{-1})
H_{br} = L.W. Back Rad. (2400-3600 Btu ft^{-2}day^{-1})
H_e = Evap. Heat Loss (2000-8000 Btu ft^{-2}day^{-1})
H_c = Cond. Heat Loss, or Gain (-320-+400 Btu ft^{-2}day^{-1})
H_{sr} = Refl. Solar (40-200 ft^{-2}day^{-1})
H_{ar} = Atmos. Refl. (70-120-Btu ft^{-2}day^{-1})
H_n

NET RATE AT WHICH HEAT CROSSES WATER SURFACE

$$H_n = (H_s + H_a - H_{sr} - H_{ar}) - (H_{br} \pm H_c + H_e) \text{ Btu ft}^{-2}\text{day}^{-1}$$

H	Temp. dependent terms
Absorbed radiation independent of temp.	$H_{br} \sim (T_s + 460)^4$ $H_c \sim (T_s - T_a)$ $H_e \sim W(e_s - e_a)$

FIGURE 5. MECHANISMS OF HEAT TRANSFER ACROSS A WATER SURFACE

2.6.1 Heat balance

The surface heat balance illustrated in Figure 5 can be written in the following form:

$$H_n = (H_s + H_a - H_{sr} - H_{ar}) - (H_{br} + H_c + H_e)$$

$$H_n = (H_R) - (H_T) \qquad (1)$$

where: H_n = net surface heat exchange,

H_R = total absorbed radiation (independent of surface temperature),

H_T = water surface temperature dependent terms.

The remaining terms are defined in Figure 5.

When the temperature of a water body is increased by the addition of heat from a thermal discharge, H_T increases and the net heat dissipation to the atmosphere taking place as H_n becomes negative.

The individual components of the total absorbed radiation term (H_R) can be computed for a specific location from basic meteorological data. The information required includes latitude, time of the year and the day, cloud cover, and humidity. Computations for the estimation of incoming solar radiation (H_s) are presented by Kennedy (1949), for long-wave radiation (H_a) from the atmosphere by Swinbank (1963), and for the reflection of solar radiation (S_r) at water surfaces by Koberg (1964). The reflection of long-wave atmospheric radiation (H_{ar}) at the water surface is a minor component of the overall heat balance and can normally be neglected.

The three components of the water surface temperature dependent term (H_T) can be evaluated in detail if air temperature and other meteorological data are available.

Back radiation from the water surface (H_{br}) is a fourth-power radiation process following the Stephan-Boltzman equation with constant emissivity.

Conduction of sensible heat (H_c) from the water surface to the atmosphere depends upon the air temperature gradient at the water surface (Table 2, Equation A). This quantity is very difficult to

TABLE 2. SOME BASIC HEAT TRANSFER EQUATIONS

Equation No.	Equation	Remarks
A.	$H_c = C_o (T_s - T_a)$	H_c = heat conducted across water surface C_o = a function of wind speed defined by equation C. T_s = surface temperature T_a = air temperature
B.	$H_e = f(w) (L_s - L_a)$	H_e = heat transferred by evaporation $f(w)$ = wind speed function discussed in Appendix A L_s = vapour pressure at surface L_a = vapour pressure in air
C.	$C_o = C_c f(w)$	C_c = Bowen's coefficient
D.	$H_n = \frac{dH_n}{dT_s} (T_s - E)$	H_n = net heat transfer at surface $\frac{dH_n}{dT_s} = K$ = surface heat exchange coefficient E = equilibrium temperature
E.*	$E = \frac{(H_s - H_{sr})}{K} + T_d$	T_d = dew point temperature
F.	$K = 15.7 + (B + 0.26) f(u)$	K has units of Btu/ft^2/day/$^{\circ}$F
G.	$f(u) = 70 + 0.7u^2$ $B = 0.255 - 0.0085T + 0.000204T^2$ $T = (T_s + T_d)/2$	u = wind speed (mph) T_d = dew point temperature ($^{\circ}$F)

* Discussed in Appendix B

estimate and for practical purposes the gradient is defined in finite difference form.

The evaporation term (H_e) in the heat balance equation becomes the major component of the cooling process in shallow water bodies having large surface areas, such as cooling lakes and ponds. The process of evaporation (discussed in detail in Appendix A) from the water surface is similar to that of heat conduction. Evaporation is controlled by the vapour pressure gradient at the surface (Table 2, Equation B). Bowen (1926) proposed that the sensible heat has a linear relationship to the evaporative heat. However, it should be noted that the use of the Bowen ratio in heat balance studies for periods of time of less than one day may not be valid. It can be shown, using the Bowen ratio, that the proportionality constant (C_o) in Equation A is a function of wind velocity (Table 2, Equation C, and Edinger et al, 1974).

Once the terms on the right-hand side of Equation (1) have been established, the estimation of the net rate of surface heat exchange follows directly. The lengthy analysis of the components of the heat balance for the determination of net heat exchange is simplified by the introduction of a hypothetical water surface temperature called the equilibrium temperature (Appendix B).

2.6.2 Hydrothermal modelling

Hydrothermal modelling involves the solution of the equations defining the hydrodynamics and heat transport processes in a water body. Although the complexity of the problem is evident from the previous discussion, the mathematics of fluid flow and heat conservation in three dimensions can be stated concisely in six equations and six variables. These six include equations for momentum in three coordinate directions, the continuity of mass, the conservation of heat, and an equation of state. Unfortunately no economical general solution or computational technique that would allow the direct use of the full set of equations is presently available. Consequently, simplifying assumptions are applied. However, no single set of assumptions are uniformly valid throughout a water body. Therefore, the current practice in modelling thermal discharges is to divide the water body into zones possessing distinct properties. Three zones (or scales) of analyses are common:

1. Near field - localized discharge region in which the characteristics of the discharge influence the flow behaviour and surface heat losses are negligible.
2. Intermediate field - in which advection and dispersion of heat by ambient currents and turbulence dominate.
3. Far field - large scale region concerned with the total heat budget of the water body.

Hydrothermal models can be classified, as shown in Table 3, according to the scale of processes involved and the number of dimensions over which temperature variations are important. Most of the models in the near and intermediate field categories, and a few in the far field, have analytical solutions suitable for use in preliminary analyses. Others require more elaborate solution techniques. Regardless of the solution method used, it must be realized that the actual physical processes themselves are not yet completely understood. Consequently, the accuracy of the results is inherently limited in most practical applications.

2.6.3 Near field modelling

Two-dimensional jet discharges are considered to be vertically mixed throughout a constant water depth and to expand laterally by entrainment through the sides of the jet. Properties of the velocity field, dilution and temperature distribution are based on the linear expansion law of momentum and heat conservation within the jet. Two-dimensional jets apply where the depth of the receiving waters is small relative to the depth of the discharge structure and when the density Froude number of the discharge is large enough for buoyancy to be neglected. Several special cases have also been formulated, for instance, for jets subject to cross-currents or bottom impingement.

Three-dimensional and buoyant jets allow for both vertical and lateral entrainment of dilution water. In the instance of a shallow discharge, vertical entrainment occurs across the underside of the plume.

TABLE 3. CLASSIFICATION OF TYPES OF MODELS IN HYDROTHERMAL ANALYSIS

Scale	One-Dimensional Cases	Two-Dimensional Cases	Three-Dimensional Cases
1. Localized discharge design		a) Plane jet b) Plane jet with friction c) Deflected jet d) Stratified discharges e) Effects of oscillating currents	a) Axisymmetrical jet b) Buoyant jet c) Deflected jet d) Submerged buoyant jet, single port e) Submerged buoyant jet multiport f) Effects of oscillating currents
2. Intermediate mixing cases	a) Simple river dilution b) Sectionally homogeneous estuary dilution c) Sectionally homogeneous & one-dimensional dispersion relationships, including oscillating currents	a) Longitudinal advection with lateral dispersion, no shoreline effect b) With shoreline c) Bounded two shorelines d) Longitudinal advection with vertical dispersion, bounded e) Other combinations of boundary conditions f) Above with computer velocity fields including oscillating currents	a) Longitudinal advection, lateral & vertical dispersion, no shoreline b) With shoreline c) Other combinations of boundary conditions d) Above with computer velocity fields including oscillating currents
3. Large scale and time-varying distributions	a) Advection with heat exchange, cooling lakes & simple river b) Sectionally homogeneous estuary c) Sectionally homogeneous analysis with time varying hydraulics d) Planar homogeneous lakes & reservoirs e) Stratified flows	a) Longitudinal & lateral advection & dispersion with two-dimensional hydraulics b) Two-dimensional planar flows with stratified interface c) Two-layered approximations to estuarine circulation & cooling lake convection d) Hydrodynamics of longitudinal & vertical motions with buoyant convection	a) Generalized three-dimensional hydrodynamic problem, including buoyancy & convection b) Merger with other scales

High initial momentum and vertical buoyant rise are the prime causes of dilution from all directions into deep submerged jets.

In general, the initial mixing processes are limited by the amount of dilution water available as a result of ambient currents and bulk water movements and also by the confines of the physical boundaries. A variety of useful models covering the majority of near field circumstances of practical interest are presented in Edinger et al (1974). In addition, Shirazi and Davis (1972, 1974) have developed many empirical relationships for both surface and submerged outfalls, based on laboratory and field observations. The primary outputs of the near field models are the idealized dimensions of the plume and the jet centreline trajectory in the vicinity of the discharge.

2.6.4 Intermediate field modelling

Vertically integrated numerical models applied over fine grid systems can be useful in describing the intermediate scale processes. Scaling relations derived by imposing simplifying assumptions concerning water body geometry, ambient velocities and dispersion on the general heat balance equation are also of interest. Two-dimensional analyses apply when heat is initially mixed vertically, then carried longitudinally and dispersed laterally, or when heat is initially mixed laterally and subsequently dispersed vertically. Three-dimensional solutions assume initial point sources to be advected longitudinally while mixed laterally and vertically. Algebraic formulations corresponding to specific idealized boundary conditions have been developed for most practical situations and are presented in Edinger et al (1972). In practice, the intermediate field processes are often not treated separately, but in conjunction with the far field.

2.6.5 Far field modelling

Large scale processes predominate when the heat extends over sufficient area that surface cooling becomes significant. Therefore, temporal variations in meteorological conditions, heat storage, heat sources and advective and dispersion processes become important in far field analyses. Many analytical models have been developed based on rather restrictive simplifying assumptions rendering them useful for first approximations only. Numerical formulations allow for more realistic time and spatially varying boundary conditions, velocity fields and for stratification. Models in this category generally deal with the numerical integration of the heat transport equation in two dimensions, with averaging being applied over the third dimension. While three-dimensional models are more realistic in principle, they are presently impractical.

In the analysis of small water bodies, the overall heat budget becomes of prime importance. Consequently, the models of far field or large scale processes predominate. Usually, the far field effects can be accounted for satisfactorily without much dependence on the details of the initial processes. Consequently, the discussion of modelling in the following sections deals principally with far field models.

3. HEATED DISCHARGE MANAGEMENT IN SHALLOW NON-STRATIFIED LAKES, PONDS AND COOLING RESERVOIRS

3.1 Introduction

Shallow non-stratified water bodies have been used for many years to effect the removal of waste heat by the basic processes of radiation, conduction and forced evaporation. There are basically two alternatives available when considering the use of shallow bodies for cooling thermal discharges. Stations can be located on existing shallow lakes or reservoirs supporting an indigenous aquatic community, or stations can be sited to use offstream, man-made cooling ponds where no aquatic life is initially present. Thus, offstream ponds can be constructed expressly for the purpose of economically maximizing the thermal efficiency of the plant and aquatic problems are then considered minimal. On the other hand, an environmental study will usually be required to determine the effect of cooling alternatives on the aquatic life in existing lakes and reservoirs or onstream systems.

The alternative of constructing a new onstream impoundment expressly for cooling may or may not be biologically important. As was mentioned in Section 2 (U.S. EPA proposed guidelines), if the cooling reservoir is located on an intermittent stream of little biological importance, then it may be considered in the same biological category as an offstream pond. If the location of the reservoir is such that the impoundment or the stream being dammed may be required to support a viable aquatic population, such as fish that are stocked, then the design must consider biological constraints similar to those existing water bodies.

An increasing interest in the use of offstream, man-made ponds compared to already existing water bodies is also due to: lower construction costs where soil conditions permit; their action as a settling basin for dissolved solids; pump power requirements are usually low, and; except for hot dry areas, little surface blowdown is required and thus they can operate for extended periods without make-up water. On the other hand, there are disadvantages such as low heat transfer waters necessitating large water body areas, fogging and icing of nearby roads, and a tendency to concentrate dissolved solids.

The advantage of some new onstream cooling reservoirs is that they may be beneficial for other purposes such as recreation, river flow control, or aquaculture of hardy fish species. However, as in the case of natural lakes or reservoirs, possible weed and algae growth may lead to subsequent maintenance problems or water temperatures may exceed tolerances of existing or proposed aquatic species.

In the United States, the latter two disadvantages attracted the concern of the EPA, which legislated that only offstream cooling, such as man-made ponds, could be considered as an alternative. There has, however, been a partial reversal in recent EPA position and it is now considered environmentally advantageous to use onstream reservoirs in the upper reaches of biologically inactive streams for cooling purposes. In Canada, on the other hand, it has been relatively common to use onstream cooling reservoirs, and if a trend can be discerned, it appears to be toward their continued use. In the only well-studied instance of a natural water body (Wabamun Lake) being used for cooling, the utility is now turning to offstream cooling ponds.

Considering the physical characteristics, the approach to hydrothermal modelling, and the waste heat management alternatives available, there are no major differences between shallow man-made cooling ponds and shallow natural water bodies. The only difference lies in the aquatic populations each supports. Existing water bodies may be expected to contain species to be protected and a major objective in the design and selection of alternatives may be to protect the species indigenous to the site. On the other hand, man-made ponds or onstream cooling reservoirs may or may not be required to support aquatic life, and the selection of alternatives and their design may be affected by this.

The following sections discuss, in general, the management alternatives available, examples of these alternatives in Canada and the United States, and an approach to modelling and determining the biological effects of heated discharge in shallow water bodies.

3.2 Management Alternatives

For one, shallow water bodies can be operated on a closed-cycle or an open-cycle cooling mode. The closed-cycle mode is essentially a recirculating mode which usually results in higher mean water temperatures, more efficient cooling, and increased evaporation and makeup requirements. The open-cycle mode is virtually the same as a once-through system. Depending upon the pond configuration and intake-outfall alternative, they can be operated in either the open or partially closed mode. During some seasons, the pond may be run partially open-cycle with a portion of the pond outlet water returned to the plant along with make-up water. During severe environmental conditions, the pond may be operated closed-cycle with allowance, of course, for blowdown and evaporative make-up water if the severe conditions are prolonged.

Offstream man-made ponds are usually designed for closed-cycle operation. They are usually regular in shape and in bottom configuration, are perched on an impermeable layer, and may include a system of internal dykes to minimize the potential for recirculation short-circuiting and to effectively use the entire free surface of a shallow lake for cooling. Open-cycle offstream ponds are usually designed as helper cooling. In both of these situations, the ponds average about 10-15 feet in depth and withdraw make-up water from an adjacent natural source.

Shallow natural water bodies or cooling reservoirs are likely to have an irregular shoreline and bathymetry, and the average depth is usually less than 20-25 ft. Depending upon the size and configuration, they may be considered for either open or closed-cycle operation and may also be dyked. Make-up water is usually supplied by natural inflow to the pond but may also be pumped from other water bodies. Those plants situated on natural or artificial lakes with irregular shorelines generally draw intake water directly from a side arm, or from a side arm via a short intake canal. Discharges are usually transported to a distant part of the lake via a long discharge canal to minimize short circuiting of flows to the intake. Withdrawals and discharges from canals tend to be low velocity compared to equivalent pipe flows. Onstream cooling reservoirs are normally created by building low dams on existing streams and their construction usually takes advantage of the natural topography. In general, these man-made lakes serving as multi-purpose facilities (i.e. cooling, fishing, boating, etc.) are larger than required for simple cooling.

Figure 6 illustrates a generic schematization of some of the more common management alternatives for use in shallow water bodies, with a listing of some stations employing these alternatives. In general, the intake-outfall design alternatives for shallow lakes and cooling ponds are basically limited to variations of a surface intake combined with a surface discharge.

3.2.1 Examples of Alternatives

There are several Canadian thermal stations situated on small lakes, ponds or reservoirs which may be classified as non-stratified cooling water bodies. The majority use long open canals to carry the waste heat to low velocity surface discharges or very shallow submerged discharges. Similarly, most of the intakes are at the surface near the plant and have open canals leading in from the shoreline. Some of the technical aspects of these stations are summarized in Table 4, which also includes the Grand Lake station on a stratified water body.

The alternative with an intake located near the plant and the discharge being carried by a larger, open canal to an upstream location is presently used at both the Maccan Station and the Battle River Station in Canada. The 26 MW Maccan Station in Nova Scotia is sited on Harrison Lake which is about one and three-quarter miles long and one-half mile wide. The level of this 450-acre lake is regulated by a small sluice gate. The intake is flush with the shoreline and draws directly into the plant from the surface. The once-through cooling system discharges through a dual outfall canal system. During the summer, the cooling water is discharged into a 500-foot long canal which eventually exits below the plant. In the winter, a large portion of the heated water is intentionally recirculated, to keep the intake clear of ice, through another canal which discharges upstream of the plant.

The small cooling reservoir for the 365 MW Battle River Station in Alberta is about three miles long, one-third of a mile wide, and reaches a maximum depth of 25 feet at the dam. The intake is near the dam and is a submerged open pipe. The condenser cooling water is directed upstream in a one-mile long open canal and is discharged at the surface.

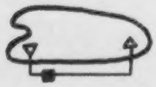
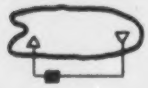
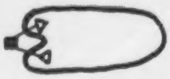
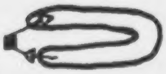
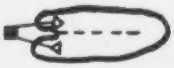
Alternative		Stations - Locations
Long Outfall - Short Intake		Poplar River Stations (Units 2 & 4) Saskatchewan, Smithers Lake, Parish Plant Houston, Texas Wilkes Lake Station, Texas Fairfield Reservoir, Texas North Lake Steam Station, Texas Battle River Station, Forestburg, Alta. Maccan Station, Harrison L, N.S.
Long Intake - Short Outfall		Concho Plant, Lake Nosworthy, Texas
Partially Separated Intake & Outfall		Sundance Station (former), L. Wabamun, Alta. Wabamun Steam Station, L. Wabamun, Alta. Four Corners Cooling Pond, Farmington, N.M. Mt. Bayou Lake Bastrop, San Gideon Plant, Texas Handley Station, Lake Arlington, Texas Montrose Reservoir Station, Missouri
Intake & Outfall on distinct portions of same body (or dyked)		Mountain Bayou Lake, Coughlin Station, Louisiana Atikokan Station, Ontario Regina Steam Station, Wascana L., Saskatchewan Par Pond, South Carolina
		LaSalle Cooling Pond, Chicago, Ill. Sundance Cooling Pond, Alberta Numerous offstream cooling ponds Challa Cooling Pond, Holbrook, Arizona

FIGURE 6. GENERIC SCHEMATIZATION OF MANAGEMENT ALTERNATIVES

TABLE 4. SOME THERMAL ELECTRIC GENERATING STATIONS ON SMALL LAKES, RESERVOIRS AND PONDS IN CANADA (Steam electric generation of 20 MW or More)*

STATION	LOCATION	GENERATION	FUEL	UTILITY	TYPE OF COOLING	COOLING WATER DEMAND (cfs)	COOLING WATER - INTAKE SOURCE OUTFALL BODY	INTAKE DESCRIPTION	DISCHARGE TEMP. RISE °F (°C)	OUTFALL DESCRIPTION	REMARKS
Grand Lake Power Station	N.W.shore of Grand Lake at Newcastle Creek, N.B.	100	coal	New Brunswick Electric Power Commission	once through	225	Grand Lake	open channel≃ 250' long, from lake surface	16-18 (8.9-10)	canal ≃ 350' long to lake surface	cofferdam to prevent recirc.
Boundary Dam	Estevan, Sask.	882	coal	Sask. Power Corp.	once through	402	Boundary Dam Res.	submerged ≃ 40' downstream of outfall	20 (11)	1-1/2 mi.long canal to submerged outfall (40') upstream of intake	-
Poplar River (under construction)	Coronach, Sask.	300-1200	coal	Sask. Power Corp.	once through	301/unit	E. Poplar R. Res.	submerged ≃ 3' below min. Level 30' below max. level at mid point of reservoir	22 (12.2)	two 2-1/2 mi.long canals to surface discharge. Three units to upper end, first unit to downstream end	On line 1979
Battle River	Forestburg, Alberta	365	coal	Alberta Power	once through	500	Battle River Res.	submerged ≃ 25', open pipe, at downstream end of res.	16 (8.9)	open canal 3/4 - 1 mi. long, surface discharge at upstream end of res.	-
Maccan Generating Plant	N.W. shore, Harrison L. N.S.	26.5	coal	Nova Scotia Power	once through		Harrison Lake	shoreline intake at the surface	10 (5.6)	two canals ≃ 500' long, discharged below plant in summer and above in winter	-
Wabamun Power Plant	North shore, Lake Wabamun, Alberta	582	coal	Calgary Power	once through	430-730	Lake Wabamun, Kapasiwin Bay	open canal ≃ 2200' long, surface intake	17-30 (9 - 16.7)	open canal ≃ 2900' long, surface discharge	used cutting of aquatic plants
Sundance (former)	South shore, Lake Wabamun, Alberta	600	coal	Calgary Power	once through	500-333	Lake Wabuman, Goosequill Bay	open canal 2100' from surface, piers project into lake	17-28 (9.4-15.6)	open canal 3600' long to surface	aquatic plant growth
Sundance (present)	South shore, Lake Wabamun, Alberta	600 to future 1350	coal	Calgary Power	650 acres closed cyc cooling pond	73	N.Saskatchewan R. make-up and blowdown	river intake with small Forebay, piped to pond	11-6.1	blowdown piped to N. Sask. River, submerged pipe	fogging
Marmion Lake (planned)	Marmion Lake, Ontario	1200		Ontario Hydro	closed cycle cooling lake	-	-	-	18- (10°C-7)	-	-
Regina Steam Station	Regina, Sask.	65 steam (88 total)	oil & nat. gas	Saskatechewan Power Corp.	once through (recirculating type)	161	Waskana Creek	shoreline intake	10-12 (5.6-6.7)	submerged outfall upstream of plant	aquatic plant problems

At both of these stations, significant vegetation growth, as well as other floating debris, has caused clogging problems at the intake screens. There have been reported fish mortalities from exposure or cold shock.

The 170 MW Wilkes Lake station in Texas uses a similar cooling alternative. The cooling water intake is on a side arm of the 900 acre lake, while discharge is through a six-mile canal to the far end of the lake. Numerous biological studies indicated that fish congregated in the outfall canal during the winter, and that the species composition had turned to parasitic species. Other problems, such as oxygen depletion and species diversity changes, have been noted in the areas of these long discharge canals.

The Wabamun and Sundance stations on Lake Wabamun in Alberta have used the alternative of both relatively long intake and discharge canals, with separation provided by a headland between the canals. The heated discharges from these plants were formerly concentrated in two small bays averaging 13 feet deep, which have been the subject of detailed multidisciplinary attention.

The 582 MW Wabamun Power Plant uses once-through cooling and an open channel for both the intake and outfall. The intake flow requirement varies between 430 cfs in winter and 730 cfs in summer and there is some intentional recirculation to avoid frazil ice. The intake canal is about 2700 feet long and projects about 900 feet into the lake. The condenser temperature rise varies between 16.7°C in the winter and 9.4°C in the summer. The outfall canal is about 3500 feet long and also extends about 1000 feet into the lake.

Until this year, the 975 MW Sundance Plant also used a once-through cooling mode and discharged to the lake. However, in response to environmental problems, such as weed growth, and a proposed increase in the size of the station, Environment Alberta recently requested Calgary Power to abandon once-through cooling at this plant. In December, 1975, the station switched to a recirculating cooling system on a 1200-acre dyked cooling pond. The North Saskatchewan River is used as the make-up and blowdown source for this pond. The pond may be expanded or may use spray modules for future units at Sundance. Prior to construction of the offstream cooling pond, the intake canal was 3400 feet long and was protected by 800 foot long piers that projected into the lake. The cooling water flow varied between 833 cfs in the summer and 500 cfs in the winter, and the corresponding outfall temperature rises were 9.4°C and 15.6°C, respectively. The outfall was a 4200 foot open canal that discharged at the shoreline.

The 525 MW fossil-fueled steam plant on the shallow 1600 acre Montrose Reservoir in Missouri uses a cooling system similar to those on Lake Wabamun. In this case, the discharge canal is about 3000 feet long and the intake canal about 1500 feet long. Brezina et al (1970), in an investigation of water quality in this shallow lake, noted the most significant effect of the heated discharge to be considerable recirculation between the intake and outfall, and that higherconcentrations of dissolved solids (than those recorded in other Missouri reservoirs) resulted from forced evaporation.

The alternative of separating the intake and outfall by siting them in distinctly separate portions of the same water body is illustrated to advantage by the 420 MW Coughlin Station on 650-acre Mountain Bayou Lake in Louisiana. Although the intake and outfall are separated by about 3000 feet, the heated discharge enters a side arm of the shallow lake and then must travel over 13,000 feet to the intake.

The 88 MW Regina Steam Station (65 MW steam) uses a similar alternative with long intake and discharge conduits. At this station, facilities are also provided to draw the cooling water from two shoreline intakes immediately at the plant as well as another shoreline intake in a downstream pond. The station is located on the upper pond of Wascana Lake Reservoir which is about two miles long, one-third of a mile wide, and six feet deep at the plant. The outfall is carried by a submerged pipe to a point upstream of the plant. Although this intentional recirculation avoids winter icing problems, weed growth and heat build-up are problems in the summer even when the shoreline intake in the lower pond is used.

The use of dyking to separate the intake and outfall is usually only found in offstream cooling ponds, such as at the Sundance plant in

Alberta. These systems use one dyke or several dykes, such as at the 2400 acre cooling pond for the 2000 MW LaSalle County Nuclear Power Plant in Illinois. The maximum cooling water flow is 6100 cfs with a temperature elevation of 13°C (24°F). The lake has an average depth of about 13 feet and is partially bound by a natural shore. The heated discharge is directed an "S" shaped path within the lake by two dykes running almost the length of the pond. Another interesting example is the 380-acre Challa pond at the 115 MW Holbrook Station in Arizona. This pond was constructed by placing a dyke on three sides while taking advantage of the local topography and soil conditions on the other side. In addition, the pond is divided into two sections. The "hot pond" area near the discharge is separated from the "cold pond" by an inverted weir about five feet high. The weir helps prevent short-circuiting of the heated effluent from outfall to intake when wind conditions favouring recirculation occur.

A long flow path to avoid recirculation can, however, be provided in undyked ponds. For example, field measurements at the open 1200-acre Four Corners cooling pond in New Mexico (Currier et al, 1974) indicate that the mean flow path is about three miles.

3.3 Hydrothermal Considerations

The ambient temperature of shallow lakes, ponds and reservoirs with limited inflow varies with the annual meteorological cycle. These temperature variations are largely in response to changes in solar radiation and humidity. In the event that a thermal effluent is discharged into the water body, the annual water temperature will tend to be raised essentially by a constant value. This results in uniformly increased average temperatures throughout the year. However, due to the rapid response of shallow water bodies to meteorological variations, in many cases the natural diurnal temperature changes are still a significant factor, and in some cases remain more significant than the thermal input from a plant.

3.3.1 Heat dissipation

Because the dissipation of heat is primarily a surface phenomenon, the heated discharge is usually released at the pond surface where it spreads out over a wide area. Cooling ponds principally dissipate heat by radiation, evaporation and conduction from the free surface. Ponds have relatively low heat transfer rates and, therefore, require extensive surface areas. The total evaporation is substantial, but there is little that can be done in the cooling system design to minimize the consumptive water loss. If this increase in total evaporation is sufficient to upset the natural evaporation-precipiation inflow balance, it may be required to supply additional water from an outside source or examine another cooling system such as cooling towers. Since ponds normally operate at temperatures below those of cooling towers, they rely less heavily on evaporative heat transfer and more on conduction of heat and, consequently, do not consume as much water as do towers for the dissipation of an equivalent amount of excess heat. However, the sum of forced and natural evaporation from a pond is generally greater than would be expected from a wet tower (Sonnichsen, 1975).

3.3.2 Circulation

Natural circulation in small water bodies is generally through wind action which, in many cases, may be small compared to the effects of plant discharge and pumping or the recirculation set up between the intake and outfall (whether intended or not). The pumping may also result in increased turbidity, increased rates of mud-water biochemical reaction, and subsequent dissolved oxygen depletion. The large possible differences between intake and discharge temperatures may also lead to surface density flows or induced stratification if some areas of deep water are present (Ryan, 1974). The discharge can move along the extent of the pond in the surface layer and then be recirculated back through the deeper layer to the discharge point. A high velocity discharge will induce mixing with cooler layers at the discharge end and result in an intake temperature which is a function of the discharge temperature.

Ponds and reservoirs used for cooling usually recirculate water between the condenser and the pond but require that the inlet and outfall be far enough apart to prevent significant heat buildup. The problem of temperature buildup can be handled in several ways but, as was discussed in the previous section, the usual strategy is to provide sufficient separation of the intake and outfall.

In the instance of a closed cooling pond, the objective is to eliminate short-circuiting between the intake and outfall. On one hand, the alternative of dyking or siting the intake and outfall so that a long flow path separates the two will usually solve this problem. On the other hand, the potential for short-circuiting may be avoided by the adoption of high velocity discharge at some distance from the intake to promote good mixing throughout the entire pond.

In most ponds or cooling reservoirs, it is difficult to control icing except by intentional recirculation. However, as recirculation of a large portion of the flow will subsequently increase temperatures and aggravate the evaporation problem, the best design uses a small recirculating line back to the intake or return only a portion of the discharge.

It may be concluded that the hydrothermal effect to be avoided is unintentional recirculation, because of resulting higher-than-desired temperature regimes, associated increases in evaporation, dissolved solids buildup, and increased make-up inflow requirements. The alternatives using significant separation between the intake and outfall, whether by dykes in ponds or by using the natural configuration of an existing lake, offer the best solution.

3.4 Biological Considerations

There are two fundamental differences from a biological viewpoint in the use of shallow lakes compared to rivers as a source of once-through cooling water. Firstly, since the residence time of water in a shallow lake is much greater than that in a certain reach of river, water is more likely to be recirculated in a lake than in a river. Secondly, warmed water emanating from an outfall in a lake will not mix as rapidly in the area of the outfall as it will in a river, and will thereby cause some local warming. On the other hand, there are usually no migrating fish in a lake, whose route could be "blocked" by a thermal plume, as there may be in a river.

The influx of a heated effluent always produces an impact on the biota in the heated area. The magnitude and extent of the impact depends on the complexity of the ecosystem and on the amount of heat injected into it (i.e. ΔT, mixing)

Environmental impacts arising from the injection of significant quantities of heated water into small water bodies typically comprise changes in numbers of individuals of a given species (in the form of an increase, or decrease), or shifts in species numbers to greater or fewer, or no changes in numbers of species but simply a change in taxa. Given the complexity of the interactions of the components of an ecosystem, the possible changes that can be brought about by thermal modification appear numerous. However, some important generalities or trends can be noted. For instance, if the water temperature in the vicinity of the outfall is warmed up to, but not appreciably beyond, 30°C, a typical response in an ecosystem is an increase in primary productivity with a shift in diversity index (sometimes upwards but more often downward) and a corresponding increase in productivity at higher trophic levels. Breeding seasons are advanced and maturation and growth periods may be reduced.

In temperate climates, particularly in the United States, this increase in productivity in the ecosystem of a small lake normally occurs in the winter when ambient temperatures are low and a thermal influx provides a stimulating effect on individuals and, hence, the components of the ecosystem. In the summer months, however, with ambient water temperatures relatively high (20-30°C), an influx of warmed water from a thermal plant will often cause local temperatures to exceed 30°C. At such temperatures, primary productivity may be inhibited and species shifts to more heat-tolerant forms occur. Diversity may be reduced. Concommitant changes at all other trophic levels often reflect the inhibition or reduction in activity of the entire local ecosystem.

These considerations do not imply that a "stimulation" of the ecosystem or an increase in primary productivity is necessarily a good thing. For instance, an increase in the water temperature from (a natural) 25°C to 32°C may cause a shift in phytoplankton from a predominance of diatoms (a common food source for zooplankton) to a relatively few species of blue-green algae not so widely used as food and often regarded as a "nuisance alga". Total plant production may be elevated significantly by the influence of the warm water but this change may be qualitatively detrimental. Current philosophy states that, in general, unless the biota of a small lake or reservoir are to be managed (by stocking the waters with warm-water fish, for example), the impact of a thermal effluent should be kept to a minimum.

On the other hand, if a small water body is to be designated as a "managed pond", it may not be undesirable to add some quantity of heat to it. For the Canadian situation, a chronic thermal impact might result in incurred diversity, productivity and prolonged "growing seasons" for the species that are desirable, i.e. those that are to be managed. Under these special circumstances, the effects of addition of heat may be beneficial.

3.4.1 General effects

Since the principal effects of thermal effluents are the modification of life-cycles and shifts in species abundance and composition, species which are able to fulfill all of their requirements for existence within the influence of the heated areas would be "opportunistic" while their not-so-successful competitors would be displaced by more heat-tolerant species. Any changes at the basic producer levels, that is, phytoplankton and plant production (primary) and zooplankton and zoobenthos (secondary) would result in a burgeoning effect at higher trophic levels, i.e. changes in fish species, amphibians, reptiles, birds and even mammals. Often the changes seen at higher trophic levels, particularly above the "fish" level, are not the direct effect of heat but may be secondary results of changes at lower trophic levels brought about by thermal effects.

The strategy for management of thermal discharges into small water bodies must involve strict monitoring of the changes occurring in the biota, if the water body in question is of concern as an important recreational or commercial lake. On the other hand, if the impoundment is created *de novo* for the express purpose of cooling heated effluents, i.e. an offstream cooling pond, the preservation of the biota under this circumstance is of lesser importance since important biota were not there (prior to construction of the impoundment) in the first place.

If the biota are to be preserved, as would be the case for an onstream inpoundment, e.g. a reservoir created by damming a river, then biotic changes should be kept to a minimum. Spawning areas for heat-intolerant fish, for example, would have to be protected from the highest temperatures and indeed there would have to be considerable areas of water at near ambient temperatures present at all times of the year so that fish could "escape" the effects of the heated discharge.

Some of the effects of thermal effluents in small water bodies are best exemplified by citing case studies where the biota of small shallow water bodies have been monitored in order to assess the changes brought about by the operation of a power plant using a once-through cooling mode.

Two contrasting, yet comparable, situations exist at the Savannah River Plant system in South Carolina and Lake Wabamun in Alberta, as discussed in the following sections.

3.4.2 Biological case studies

There are several thermal power generators located on the various ponds with interconnecting rivers on the U.S. Atomic Energy Commission's Savannah River Plant (SRP), South Carolina. The Par Pond system, consisting of three major cooling ponds, B, C and Par Pond, was constructed in 1958 to receive thermal effluent. Pond B has not been heated since 1964 and serves as a good control ecosystem, while most of Pond C contains extremely hot water (50°C) except for peripheral areas fed by springs where temperatures are sublethal to fish species.

Water flows from Pond C (165 acres) into Par Pond (2770 acres) and surface water temperature in Par Pond gradually decreases to near ambient temperatures at the outflow. Surface water around the inflow at Par Pond can be as warm as 34°C even in winter.

The most notable effects of heat on aquatic communities can be seen when the biota of the three reservoirs (Ponds B, C and Par Pond) are compared. The three reservoirs are distinct with respect to certain floral and faunal characteristics. A major effect is the reduction or elimination of several species of vascular plants and vertebrates, and the consequent reduction in species diversity, as temperatures are increased above 30°C. Relative abundance of most plant species was reduced in portions of the reservoirs receiving chronic thermal loading (Parker et al, 1973). Other more specific observations include the absence or reduction in number and diversity of some groups of insects [plecopterans (stoneflies), odonates (dragon flies), ephemopterans (mayflies) and trichopterans (caddis flies)] in streams in the SRP system receiving thermal effluent, which are well-represented in normal streams. Natural ambient temperatures in the SRP reservoir system vary from 9-14°C in winter to 25-37°C in summer (Gibbons et al, 1975). Insect diversity and "even-ness" indices are generally lower in thermally loaded areas (Howell and Gentry, 1974). A lower diversity of macrobenthic species is evident in heated areas (Gibbons et al, 1975). Amphibian species found in heated areas were found to develop more rapidly and the metamorphosed frogs and toads left the water at a smaller size than those in waters at natural temperatures. There was, in addition, an extension of the normal breeding season (Nelson, 1974). Turtles (*Pseudemys scripta*) from heated regions were found to have accelerated growth rates compared to those from unheated waters (Gibbons, 1970).

With regard to vegetation, some opportunistic plant species have invaded the warm water areas and have actually tended to raise the diversity index for aquatic macrophytes. In the natural swamp, 55% of plant species are woody, whereas in heated areas only 30% are woody. Consequently, there has been a shift in species types without an appreciable change in diversity index for terrestrial plants (Sharitz, et al, 1974). With the shift in types of trees and bushes found in heated areas, there was a destruction of some of the canopy and sub-canopy with an associated loss of small passerine bird species which normally inhabited the canopy. However, the creation of open marshes and standing dead trees brought an influx of new species such as woodpeckers, crows and herons. The non-aquatic birds then showed a shift in species composition without an appreciable change in diversity index (Straney et al, 1974).

There was a greater diversity of aquatic birds found in unheated regions as compared to heated areas (Brisbin, 1974). With these birds, as with many of the other higher forms of life, their abundance (or lack of it) often depends on the abundance of aquatic food species which are directly affected by thermal loading. Ducks, other birds, and mammals, of course, are homeothermic and are not directly affected by the heat.

Phytoplankton productivity (primary productivity) was found to be elevated in heated areas in winter and inhibited, due to mortality of entrained phytoplankters, in the summer months. Mortality was found to increase with increasing ΔT and entrainment time (Gurtz and Weiss, 1974).

With heated areas having temperatures 3-7°C higher than nonheated areas, juvenile largemouth bass from heated areas were found to be larger and had greater rates of growth than those from unheated areas (Bennett and Gibbons, 1974). Populations of bass were greater in heated areas compared to non-heated areas in the winter. Although bass taken from unheated waters were found to have greater amounts of food in their stomachs (lower digestion and metabolic rates) than those from heated areas (Bennett and Gibbons, 1972), the physical condition factors for both groups were similar (Bennett and Gibbons, 1974).

Lake Wabamun, Alberta, is located at a much higher latitude than the Savannah River. Consequently, the prevailing climate as well as the taxonomic variety of species present there differs substantially from the situation described above. Nevertheless, they are comparable as unstratified water bodies receiving chronic thermal loading in certain regions.

Lake Wabamun, with an area of 21,000 acres and a mean depth of 20 feet, may be considered a small unstratified lake. Biological studies have been carried out in the vicinity of the two plants there and reported for phytoplankton, aquatic macrophytes, phytobenthos, zoobenthos, zooplankton and fish.

Principal researchers and those most knowledgeable regarding the biology of Lake Wabamun and the effects of the power plants come from the University of Alberta and Beak Consultants Ltd. and are referred to in the following case studies.

As in the Savannah River reservoirs, the primary effect of thermal discharges from the two power plants appears to be a shift in the species types present in the heated areas. Typically, species which have achieved a competitive advantage by earlier breeding, faster maturation, loss of competitors through death and so on, have displaced the more temperate species. This "invasion" of heated areas by thermally "opportunistic" species, causing a taxonomic shift or shift in diversity, is the most typical result of a thermal discharge in any location.

Primary productivity of phytoplankton in Lake Wabamun has increased in heated areas near the Sundance Plant in summer (Gallup, 1971). Noton (1972) found a positive correlation between primary productivity and increased temperatures. Wheelock (1969) found that heat produced a lowering of standing phytoplankton crop except in winter months. Gallup and Hickman (1975) found the standing crops of phytobenthic communities to be substantially higher in heated areas compared to partially heated or unheated areas. Furthermore, there was a difference in the seasonal cycles and in species composition of major species of phytobenthic organisms in heated compared to control areas. The main phytoplankton species found in heated areas were from the blue-green algae group, *Oscillatoria amoena* and *O. borneti*. A reduction in diatom species occurred only in discharge canals. At all other areas, the abundance of diatoms was similar (Gallup and Hickman, 1975).

Among the zooplankton, rotifers dominate the natural community in spring and early summer while crustaceans dominate in the cooler months. There seem to be species shifts occurring but no definitive correlations have been established (Gallup and Hickman, 1973, 1975). In the benthic community, the shift in species abundance towards more Tubificidae and fewer Chironomidae and Mollusca is thought to be due to the change in habitat due to the activities involved in weed cutting, as well as to waste heat (Gallup et al, 1974).

Major effects of heat have been observed on aquatic macrophytes and fish. The dominant species of macrophytes in the lake are *Myriophyllum, Chara, Potamogeton spp. Ceratophyllum* and *Elodea*. Since 1971, Allan and Gorham (1973) have reported that *Elodea* has become the dominant plant in most heated areas, replacing species of *Myriophyllum, Chara* and *Potamogeton*. They stated that *Elodea* is successful in heated areas because it has shifted its growth and reproductive cycle forward by two months and also is able to grow better than its competitors during low light conditions, i.e. in winter, under ice. However, more investigation is required since other recent studies for Calgary Power have reported that *Elodea canadensis* will not grow directly in the heated effluent (Railton, 1976).

With regard to fish, there are five major species in the lake. They are the lake whitefish (*Coregonus clupeaformis*), northern pike (*Esox lucius*), yellow perch (*Perca flavescens*), white sucker (*Catostomus commersoni*) and turbot (*Lota lota*). Whitefish and northern pike are important for sport and commercial fishery. For whitefish, spawning is complete by October and cold water (at less than 1°C) must be available for winter egg development. Hatching occurs in the spring (Lane, 1970). In recent years, the whitefish population has been dropping and it is thought that warm water produced by heated effluents endangers spawning success (Lane 1970). The spawning success of other species, including northern pike, does not seem to be as endangered as that of whitefish.

The case studies carried out at the Savannah River Plant and at Lake Wabamun are particularly valuable because many components of the biota were studied in an attempt to formulate a composite picture of the effects of thermal effluents on small water bodies. It is because these studies were so comprehensive that they can be considered as "classical" and may be used as such.

At Lake Julian, North Carolina, a 321-acre reservoir presents a situation somewhat different from those existing at either Lake Wabamun or Par Pond. These differences are due to physical, biological and climatic differences among the three.

Heated effluent is discharged into Lake Julian such that one end of the impoundment usually exceeds 35°C while the other is normally cooler than 35°C. In the cooler waters, the area is dense with *Chara*, with a rich periphyton and benthic community. With an abundance of food in this area, sunfish species residing here were in good condition. By contrast, in the sections where the temperatures were usually over 35°C, the blue-green alga *Oscillatoria* is the dominant plant form and this characterizes a food-limited environment for fish. The four species of sunfish studied showed chronic malnutrition when they were taken from heated areas. A combination of increased metabolic demands in the fish, coupled with a reduction (killing) of food species (by exceeding upper lethal temperature limits) led to a depletion of food in heated areas and caused fish to move to cooler areas, whereupon overcrowding of the areas was prevalent (Graham, 1974).

By observing the effects of thermal effluents on aquatic biota in small water bodies, it can be concluded that, in general, significant changes can be expected to occur. It is not possible to assess the extent or magnitude of the changes without detailed studies of each case and, most importantly, without making a value judgment on whether the changes are beneficial, detrimental or neutral. If one assumes the premise that changes in the biota of a small water body will result from the discharge of heated effluent from a power plant located on that water body, then the problem resolves itself to determining or predicting the magnitude and extent of the changes and then making a judgment as to the significance of the changes as they relate to the size of the power plant. (This is discussed in detail in Section 6.)

3.5 Mathematical Modelling

Mathematical models can be used at two stages in a hydrothermal study of shallow water bodies: (a) preliminary screening phase, and (b) detailed studies. At the preliminary screening phase, the emphasis is on determining estimates of the hydrothermal regimes associated with a number of alternatives. If these alternatives are limited by biological constraints such as mentioned previously, then the area and temperatures will be required as input to the biological assessment. If the aquatic environment is not a concern, then the screening models will still be useful in the engineering economic analysis to determine the minimum area of an artificial pond and the maximum thermal efficiency. At a later stage, the application of the more sophisticated numerical models, also discussed here, is often warranted in performing detailed studies of a reduced number of alternatives. These models typically provide more detailed solutions at the expense of increased operating costs and field data requirements. In general, the appropriate model will reflect the complexities of the situation with a reasonable level of realism at an acceptable data preparation and computational cost.

The majority of existing models in the first category are steady state, one-dimensional and based on either the plug flow or fully mixed concept, although attempts have been made at addressing the more realistic cases intermediate to the above extremes at determining transient effects. Heat loss at the water surface is the main cooling process accounted for. The basic assumption commonly made is that vertical and lateral temperature gradients are unimportant relative to the longitudinal temperature profile.

3.5.1 Fully-mixed model

The closed-cycle fully-mixed steady state excess temperature model represents the most elementary cooling pond temperature excess computation. It is based on the assumption that a heated input will be mixed uniformly throughout the water body such that no temperature gradients will exist. It requires infinite mixing to occur in all directions. The model is illustrated in Figure 7 and is expressed by the formula:

$$\overline{\Theta} = H_p/KA \qquad (1)$$

where: $\overline{\Theta}$ = average fully-mixed excess temperature of water body (^oF),
H_p = plant rejection rate (Btu/hr),
K = coefficient of surface heat exchange (Btu/hr/$^oF/ft^2$)*,
A = surface area of water body (ft^2).

As an example, if a fossil fuel plant (heat rejection rate, $R_p = 3.9 \times 10^6$ Btu/hr/MW) with an installed capacity, Ge, of 500 MW is to be located on a 1000-acre regular shaped, shallow prairie lake ($K = 130$ Btu/day/$ft^2/^oF$), the average pond excess temperature will be determined by:

$$\overline{\Theta} = \frac{R_p\ Ge}{KA} \qquad (2)$$

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* See Appendix B for further discussion.

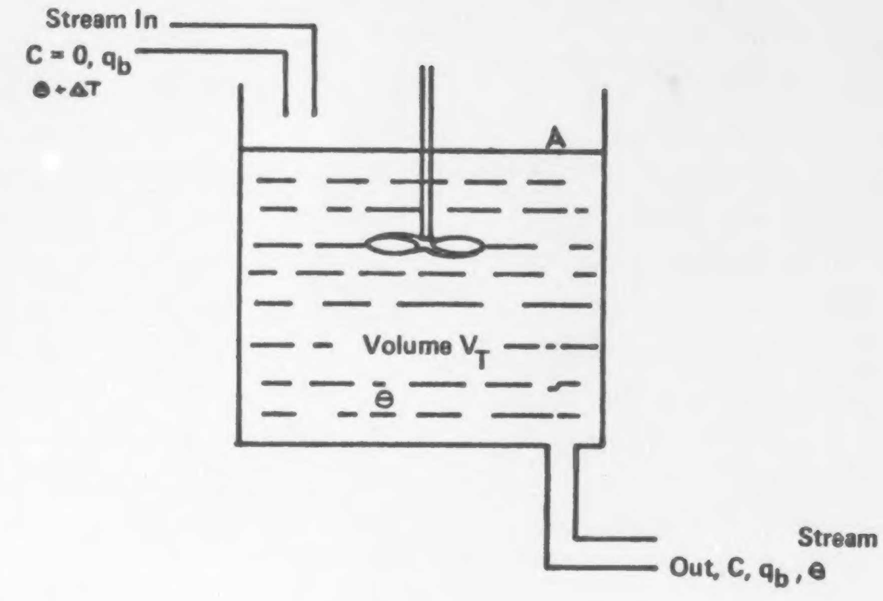


FIGURE 7. COMPLETELY MIXED MODEL

$$= \frac{3.9 \times 10^{6} (\text{Btu/hr/MW}) \times 24\ (\text{hr}) \times 500\ (\text{MW})}{130\ (\text{Btu/day/ft}^{2}/{}^{\circ}\text{F}) \times 1000\ (\text{acres}) \times 43560\ (\text{ft}^{2}/\text{acre})}$$

$$\theta = 8.3^{\circ}\text{F}$$

While the fully-mixed conditions are rarely, if ever observed in practice, the results are useful in determining limiting or extreme performance values. Under these steady state conditions, the pond reaches a temperature excess at which rate of surface heat dissipation balances the rate of heat rejection. The fully-mixed relation is also presented in nomograph form in Figure 8. In this form, quick preliminary estimates of required cooling pond area can be made for given values of plant size, surface cooling rate and acceptable limits of fully mixed temperature, or values of excess temperature can be approximated for given plants and pond dimensions.

For open-cycle fully-mixed ponds, heat is removed from the pond both by cooling at the water surface and by simple advection at the pond outlet. This can be expressed by the following formulation:

$$\overline{\theta} = H_p / (KA + Q\rho Cp) \qquad (3)$$

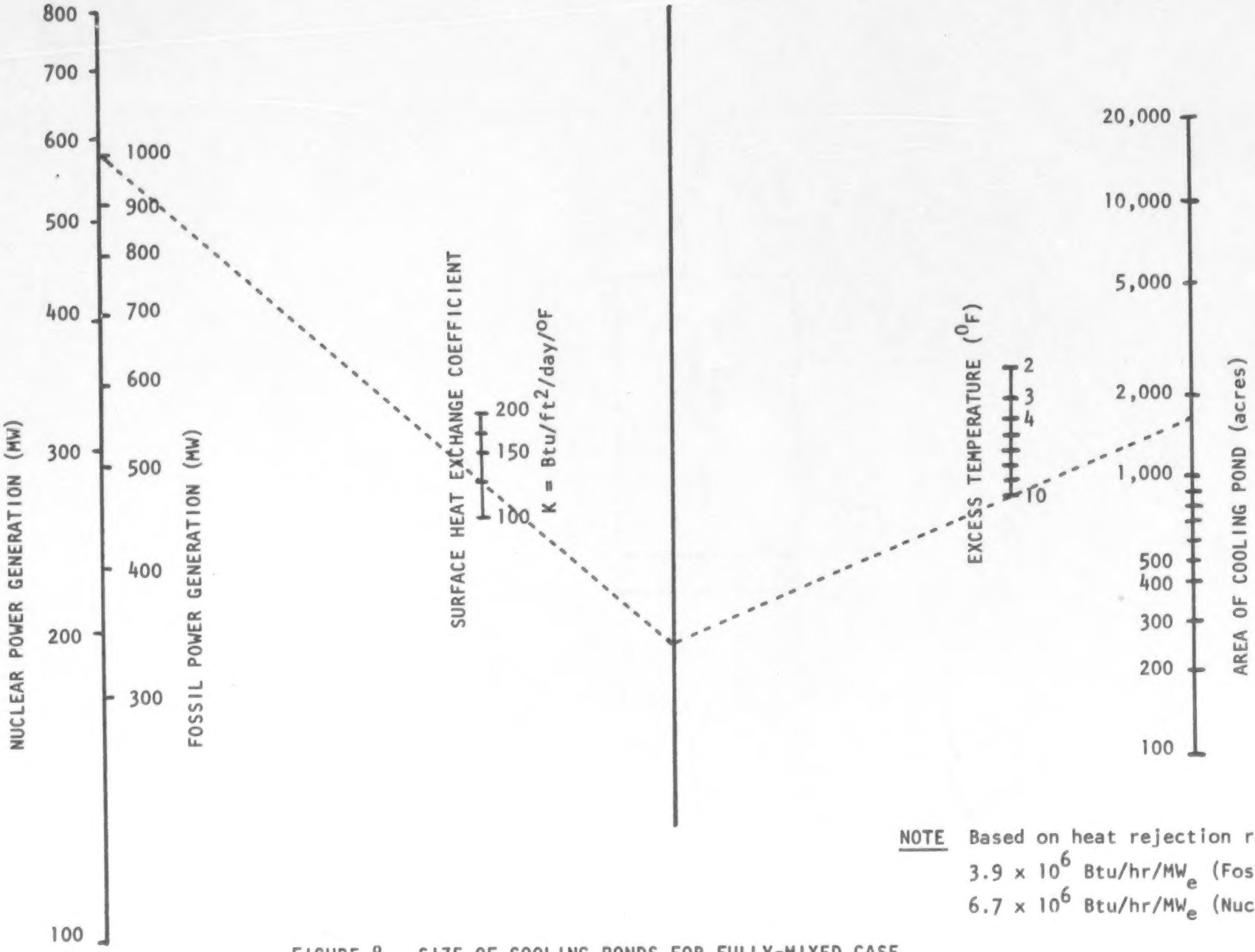
where: C_p = specific heat of water,
ρ = density of water,
Q = condenser flow rate.

3.5.2 Plug flow model

Plug flow models assume exponential temperature decay of heated discharge with increasing surface area by exchange at the water surface. In determining the excess temperature profile along the main axis of a lake, the model requires that no longitudinal dispersion take place and, thus, the performance of narrow lakes tends toward the plug flow extreme (Figure 9).

Most modellers present the steady state plug flow model for open-cycle lakes in the exponential equation (Edinger et al, 1974):

$$\theta = \frac{H_p}{\rho CQ} e^{-Ka/\rho CQ} \qquad (4)$$



NOTE Based on heat rejection rates of:

3.9×10^6 Btu/hr/MW_e (Fossil)

6.7×10^6 Btu/hr/MW_e (Nuclear)

FIGURE 8. SIZE OF COOLING PONDS FOR FULLY-MIXED CASE

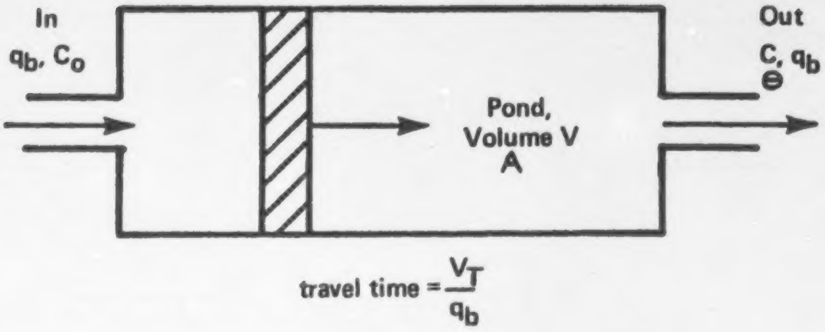


FIGURE 9. PLUG FLOW MODEL

where: H_p = plant heat rejection rate (Btu/sec),

e = excess temperature at a longitudinal distance x from the discharge (^oF),

a = water surface area between the discharge and the point x (ft^2),

K = coefficient of surface heat exchange ($Btu/sec/^oF/ft^2$),

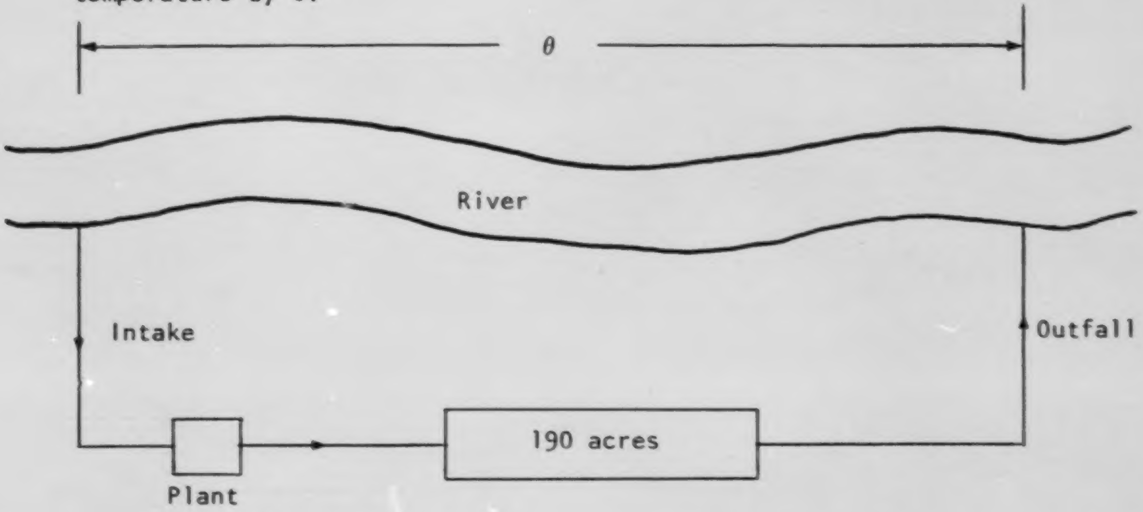
Q = flow through the water body (cfs),

ρ, C = density and heat capacity of water.

The above equation is the same as that derived for an analytical model for excess temperature in rivers.

Lateral and vertical homogeneity is assumed and longitudinal dispersion ignored. Excess temperature is shown to be a function of water surface area and independent of depth. The response of Mountain Bayou Lake to heat loads from the Coughlin Generating Station in Louisiana is typical of plug flow behaviour. The lake is particularly tenuous, as depicted in Figure 10, and quite shallow. The longitudinal distribution of observed weekly average temperatures over a six week period compares well with values predicted using the plug flow assumption (see Figure 11).

As an example of the once-through plug flow concept, consider a 230 MW fossil fuel plant ($R_p = 3.9 \times 10^6$ Btu/hr/MW) using the 190 acre elongated cooling pond shown for supplementary cooling in late summer ($K = 110$ $Btu/day/ft^2/^oF$). If the condenser cooling water flow rate is 200 cfs, the discharge temperature exceeds the intake temperature by Θ:



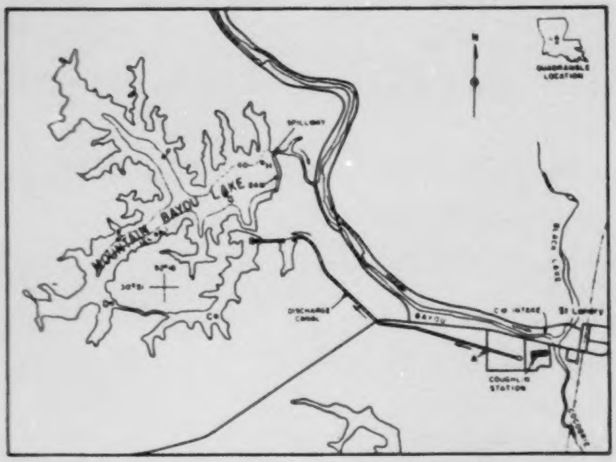


FIGURE 10. MOUNTAIN BAYOU LAKE SITE (Scale is approximately 1 inch = 6.5 miles, 1 cm = 4.1 km)

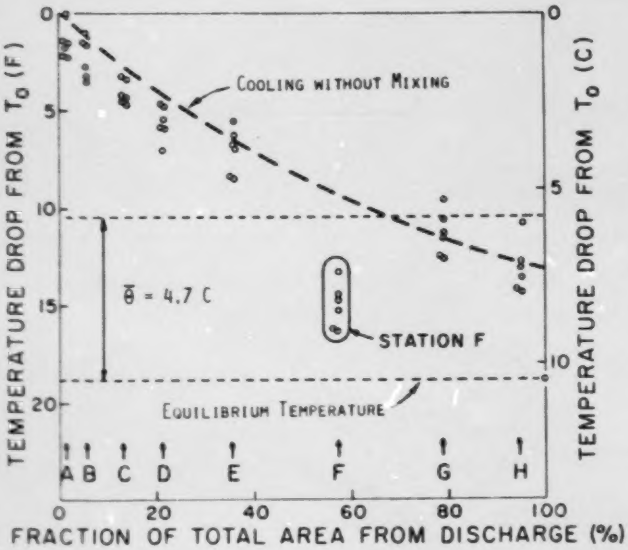


FIGURE 11. LONGITUDINAL TEMPERATURE DISTRIBUTION DURING SIX WEEKS AT MOUNTAIN BAYOU LAKE SITE

$$\theta = \frac{3.9 \times 10^6 \text{ (Btu/hr/MW)} \times 230 \text{ (MW)} \times e^{-Ka/\rho CpQ}}{62.4 \text{ (lb/ft}^3) \times 200 \text{ (ft}^3\text{/sec)} \times 3600 \text{ (sec/hr)} \times 1 \text{ (Btu/lb/}^\circ\text{F)}}$$

$$\theta = 8.7^\circ\text{F}$$

In addition, the temperature excess at any distance down the pond can be calculated by substituting the appropriate area in the equation.

The behaviour of closed-cycle ponds is complicated by the effect of intake temperature on discharge temperature. This influence can be accounted for in the equation:

$$\theta = \frac{H_p}{\rho C_p Q} \left(e^{KA/\rho C_p Q} - 1\right)^{-1} \qquad (5)$$

where: θ_i = excess temperature at intake ($^\circ$F),
A = total area of pond between outfall and intake (ft^2),

and other terms are as defined previously.

For example, consider a 1000 MW nuclear plant ($R_p = 7.6 \times 10^6$ Btu/hr/MW) recirculating cooling water at a rate of 2000 cfs through a 3000 acre "plug flow" cooling pond. If the average January equilibrium temperature is 40°F and average meteorological conditions indicate a surface heat exchange coefficient of 90 Btu/ft^2/day/$^\circ$F, the intake temperature is:

$$\theta = \left(\frac{7.6 \times 10^6 \text{ (Btu/hr/MW)} \times 1000 \text{ (MW)}}{62.4 \text{ (lb/ft}^3) \times 1 \text{ (Btu/lb/}^\circ\text{F)} \times 2000 \text{ (ft}^3\text{/sec)} \times 3600 \text{ (sec/hr)}}\right) \Big/ \; e^{\left(\frac{90 \text{ (Btu/ft}^2\text{/day/}^\circ\text{F)} \times 3000 \times 43560 \text{ (ft}^2)}{62.4 \text{ (lb/ft}^3) \times 1 \text{ (Btu/lb/}^\circ\text{F)} \times 2000 \text{ (ft}^3\text{/sec)} \times 86400 \text{ (sec/day)}}\right)} - 1$$

$$\theta = 8.6^\circ\text{F}$$

$$T_i = 8.6 + 40 = 48^\circ\text{F}.$$

Edinger et al (1974) compared typical plug flow and fully-mixed models (Figure 12). They point out that the solutions yield extreme values with real behaviour falling in the intermediate zone. The performance of

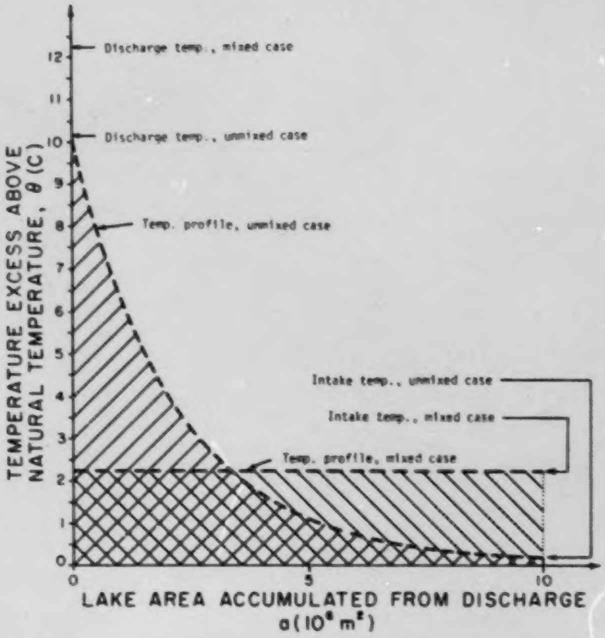


FIGURE 12. TEMPERATURES IN MIXED AND UNMIXED COOLING LAKES

narrow, tenuous lakes, in which the effects of longitudinal dispersion will be small, tend towards the plug flow extreme. Wide exposed lakes which commonly experience relatively high degrees of mixing due to counter flows, wind action, etc. approach fully mixed behaviour. Comparisons between these two approaches (Section 6) show that the excess temperature at the plant intake drawing from a fully mixed pond will be substantially higher than in the case of a plug flow pond, in spite of identical mean pond temperatures. It also indicates that the temperature of the plant discharge is higher in the fully mixed case. This, however, is not noticed in the pond itself since the discharged heat is instantaneously mixed throughout the water body.

3.5.2.1 Unsteady plug flow model. The production of electrical power and consequently the rate of heat rejection from a plant is usually unsteady and follows a diurnal cycle. Edinger et al (1968) have presented a number of simplified relationships applicable to unstratified one-dimensional plug flows as in shallow narrow flow-through lakes. Temporally varying heat loads carried in constant cooling water flows as well as averaged steady state situations are considered. The model is based on the observation that the condenser cooling water flow is normally held constant in the short term with variations in heat rejection being reflected in fluctuations in temperature rise across the condenser. Consequently the temporal span is limited to days. The difference between real time and the time of flow from the discharge location to the points of interest is considered. The model may be of use in analysing the response of small water bodies to diurnally cyclic heated discharges. While presently not computerized, the solution procedure is readily programmable.

3.5.3 Compensating for limitations of simple models

In most cases, neither the plug flow nor fully-mixed extremes are truly realistic. Many attempts at compensating for the limiting assumptions of these simple models have been made. For example, the effect of initial mixing has been considered. This becomes important when the width of the lake near the discharge is sufficient to accommodate reverse flows which bring cooled water towards the discharge point, or when stratification near the discharge is insufficient to inhibit vertical entrainment of cooler water from below. In this situation, initial mixing can significantly alter the temperature regime. Such is the case at Wilkes Lake in Texas (Geyer et al, 1968; see Figure 13) where observed initial dilution has been attributed to both the lack of summer stratification caused by short residence time and the moderate depth (15.4 feet) of the lake. Weekly average longitudinal temperature profiles observed during a six-week period are compared to predictions based on both plug flow and fully-mixed models (see Figure 14). Initial dilution gives the appearance of accelerated cooling in the discharge region with the apparent cooling rate diminishing further away.

Ryan (1971) presented an open-cycle steady state model which accounts for the effect of reverse or counter flows on initial mixing by means of a dilution factor. The general solution allows for the exponential decay of heat with increasing longitudinal surface area following the initial dilution of the inflow. This has been extended in a later

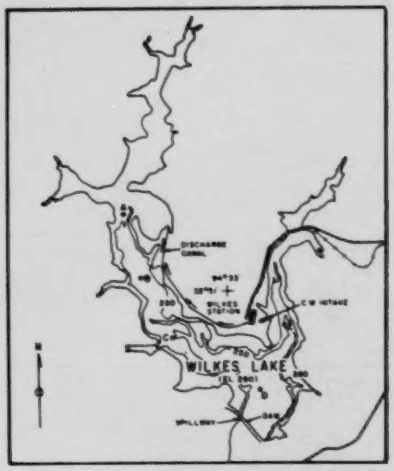


FIGURE 13. WILKES LAKE SITE (Scale is approximately 1 inch = 6.5 miles, 1 cm = 4.1 km)

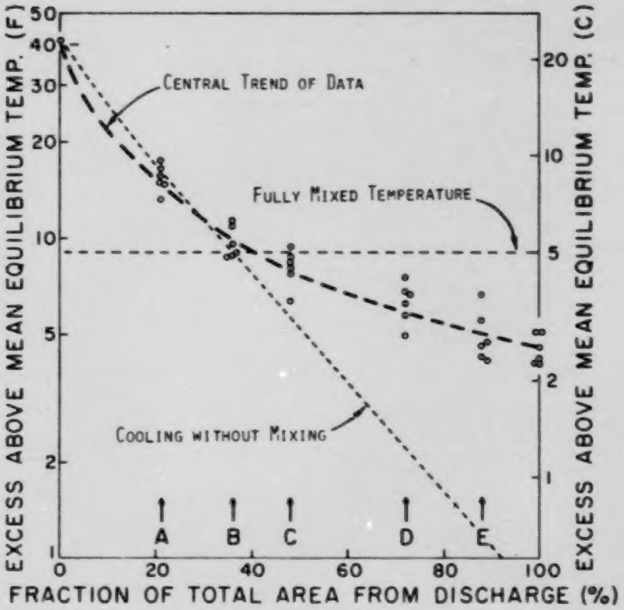


FIGURE 14. LONGITUDINAL DISTRIBUTION OF EXCESS TEMPERATURES DURING SIX WEEKS AT WILKES LAKES SITE

publication to account for the recirculation of heat through the intake experienced in continuous operations (Jirka et al, 1975). In the extremes, when the dilution factor approaches unity, or is much larger than unity, the general case approaches the classic plug flow and fully-mixed cases, respectively.

The limitation of the plug flow assumption is sometimes compensated for by the introduction of the concept of the effective surface area. Lakes often are composed of side arms and tributary embayments. The basic assumption is that these areas do not play an active role in heat dissipation. Edinger (1971) proposed a procedure whereby a shape factor or effective surface area is determined and used to modify the plug flow exponential decay equation. The lake is divided into a main flow body and side arms (see Figure 15). Plug flow is assumed in the main area, with heat diffusing into the side arms. A natural flow through the lake can be included in addition to the plant-induced flows. The reference includes a numerical example which illustrates the simplicity of its application. The technique is applicable to lakes where vertical mixing between the plant discharge and natural inflow is complete and where no substantial density underflows through the lake exist. The model may be useful in the preliminary evaluation of alternative discharge-intake locations on a lake possessing significant side arms and embayment areas.

Edinger et al (1974) presented a model capable of dealing with intermediate cases in which significant but finite degrees of longitudinal mixing exist. A disperson parameter is introduced which depends upon the coefficient of longitudinal dispersion. The assumption is made that dispersion, flow velocity, water depth and the coefficient of surface heat exchange are invariant spatially and temporally. The relationships presented in Figure 16 are based on this concept of partially mixed lakes. These can be useful in making first estimates of excess temperatures and performing sensitivity analyses on dispersion parameters (as shown in Section 6).

3.5.4 Numerical models

The screening, or analytical, models described above are useful in determining first estimates of (a) the water surface area required to dissipate heat rejected from a power plant, and (b) the water temperatures

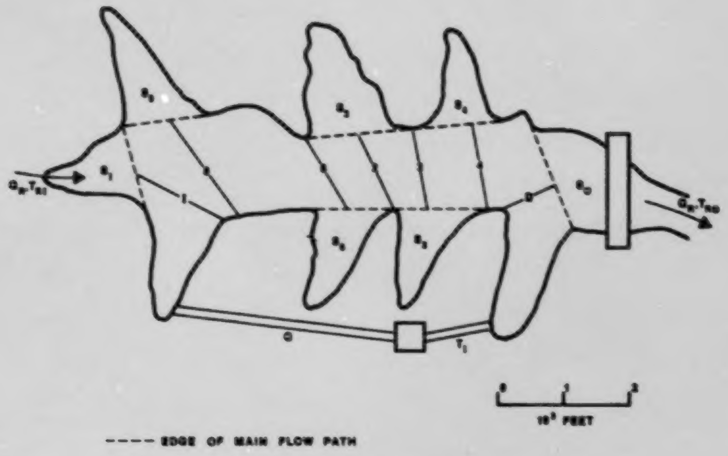
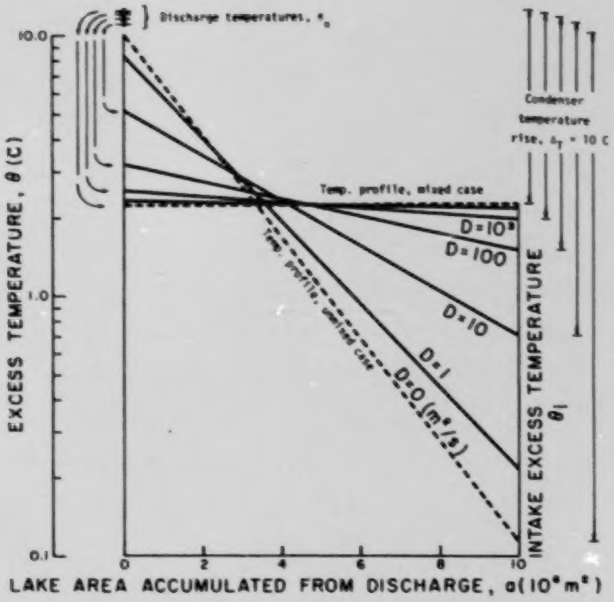


FIGURE 15. DEFINITION SKETCH FOR INFLOW-OUTFLOW FORMULATIONS



Sample data $A = 10^7$ m^2, $L = 10^4$ m, $b = 10^3$ m, $h = 10$ m,

$Q = 16$ m^3/s, $\Delta T = 10$C ($H_p = 1000$ MW), and $K = 30$ W m^{-2} C^{-1}

D = longitudinal diffusion coefficient.

FIGURE 16. EXCESS TEMPERATURE DISTRIBUTIONS IN A PARTIALLY MIXED LAKE

at the pond outlet. However, they are often unable to adequately predict the temperature distribution in space and time and the flow distribution in the water body when biological constraints are important, or when considering the possible presence of operational inefficiencies (short-circuiting, reduced effective surface cooling area). Therefore, at later stages in a hydrothermal study, it may be necessary to apply more sophisticated numerical models.

Numerical models presently deal with the transient solution of the simplified vertically integrated two-dimensional heat transport equation. Three currently available models are discussed here, including two finite difference models from Edinger et al (1972) and Yeh et al (1973), and a finite element model presented by Loziuk et al (1973). Table 5 summarizes a comparison between the three models.

All three models are capable of producing time varying solutions of the heat transport equation. They all account for heat exchange at the water surface and advective heat transport; and neglect buoyancy effects (equivalent to neglecting the dependency of density on temperature). However, they are at variance in many other respects.

3.5.4.1 Finite element model by Loziuk et al (1973). In general, one of the major advantages of the finite element solution technique is its ability to accommodate variable grid size and shape throughout the study region. Therefore, it is most useful in analyzing ponds having complicated shapes.

Loziuk et al (1973) developed a model in which both the hydrodynamics and heat transport equations are solved using the Galerkin finite element method (Zienkiewicz, 1971). The major assumptions on which the model was based were:

1. The hydrodynamics do not vary with time. This justifies the use of a steady state velocity field.
2. The hydrodynamics can be realistically represented by idealized fluid flow. Wind induced water movement and bottom friction are not included.
3. The water depth throughout the water body is considered uniform.

TABLE 5. COMPARISON OF NUMERICAL MODELS

Model	Theoretical Basis	Solution Technique
Edinger et al, 1972 (HYETA)	Velocity - 2 horizontal momentum equations with inertia terms excluded - 2-D continuity Heat- 2-D heat transport equation	Explicit finite difference
Loziuk et al, 1973	Velocity - potential function based on ideal 2-D fluid flow Heat- 2-D heat transport equation	Implicit Galerkin finite element
Yeh et al, 1973	Velocity - 2 steady state momentum equations with convective acceleration ignored - 2-D continuity - stream function	Explicit finite difference
	Heat- quasi 2-D heat transport equation - mixed Lagrangian Euler approach	Runge-Kutta method (explicit finite difference)

TABLE 5. (CONT'D)

Model	Wind Stress Effects	Variable Bathymetry	Transient Hydrodynamics	Diffusion of Heat	Initial Dilution	Transient Surface Cooling Coefficient	Evaporative Water Losses	Buoyancy Effects	Transient Temp. Solution	Compared to Field Data	Availability
Edinger et al, 1972 (HYETA)	Yes	Yes	Yes*	Yes	Yes	No	Yes	No	Yes	Yes	Nonproprietary** published listing***
Loziuk et al, 1973	No	No	No	Yes	No	Yes	No	No	Yes	Yes	Proprietary
Yeh et al, 1973	Yes	No	No	No	No	Yes	No	No	Yes	Yes	Nonproprietary

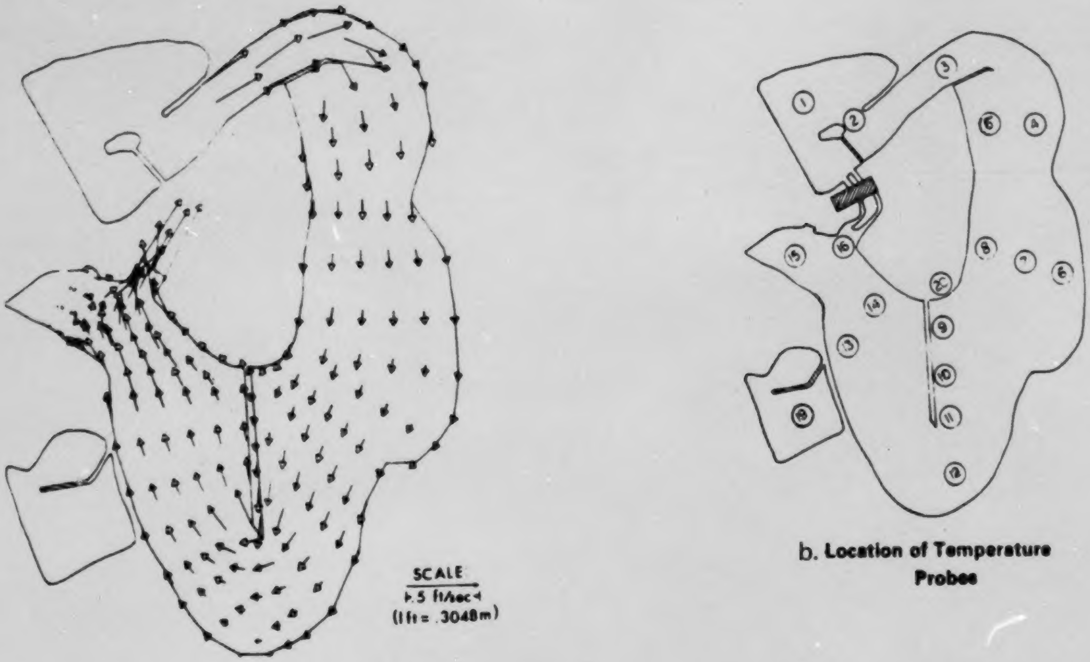
* See discussion in Appendix C.
** See Appendix C for program listing.
*** Listing of program published in Edinger et al (1972).

Diffusion of heat in the two horizontal directions is considered, as well as hourly variations in meteorological conditions and heat rejection. In order to solve the temperature field, the velocity field, diffusion coefficient, initial temperature field and the time dependent surface transfer coefficient and boundary conditions must be known. The model was applied to Horseshoe Lake in Oklahoma. The lake has an area of 280 acres and an average depth of 3.5 feet. A seven-unit generating station with a total capacity of 470 MW is located on the lake. The transient behaviour of the pond predicted by the model was compared to temperature observations recorded in a four-day monitoring effort in July, 1963. Temperatures were monitored by means of temperature probes distributed throughout the lake (see Figure 17b). During this period only two of the seven units were operating. The finite element representation of the lake is shown in Figure 17. Notice the capability of the model to realistically represent the flow near internal obstructions such as dykes (see Figure 17a). The simulated temperatures given by the model compared reasonably well to the measured values, with maximum variations occurring in the central region of the lake as opposed to near the intake and outfall (See Figure 17d). These discrepancies were attributed to localized conditions such as wind variations.

While the finite element approach of this model is very useful in analyzing ponds having complex shapes, the realism with which the geometry is to be modelled must be weighed against the difficulty in formulating the problem. At the same time, the assumption of ideal fluid flow in this model is not a particularly good one in the case of irregular shapes and depth. Consequently, while a finite element model appears useful, its attractiveness for use in the presence of complex geometries is decreased somewhat by this assumption.

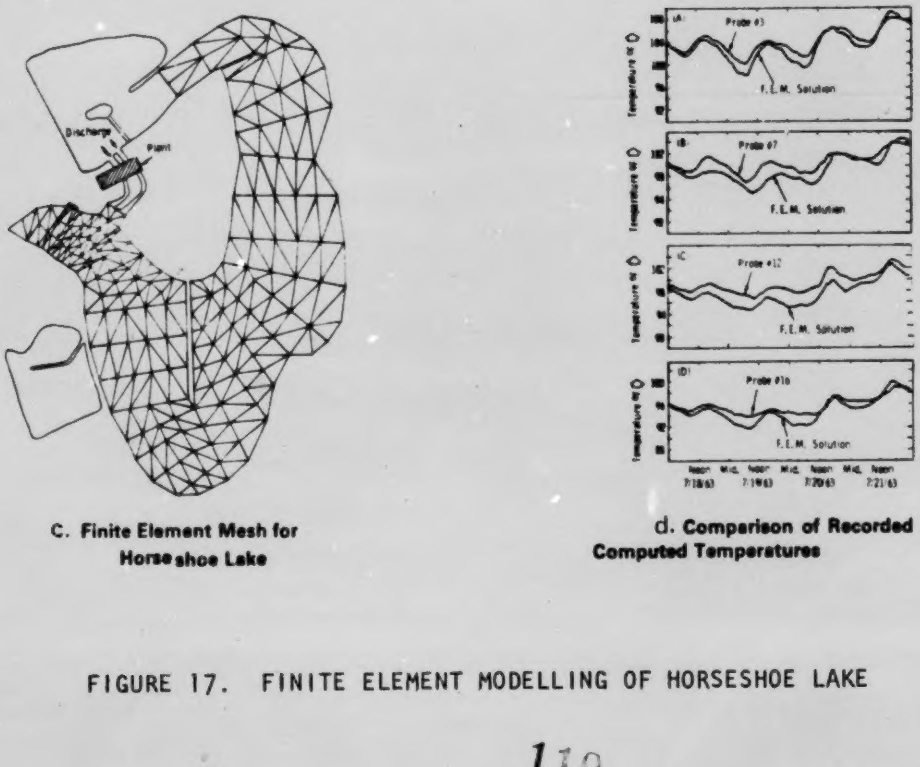
3.5.4.2 Finite difference model by Yeh et al (1973). Yeh et al (1973) developed a fully explicit finite difference model. The major assumptions and limitations particular to this model are:

1. Plant flow is normally steady, justifying the use of a steady state solution of the hydraulics.
2. The nonlinear convective acceleration terms are considered negligibly small and can safely be ignored.



a. Relative Magnitude and Direction of Velocities at Each Node

b. Location of Temperature Probes



C. Finite Element Mesh for Horseshoe Lake

d. Comparison of Recorded and Computed Temperatures

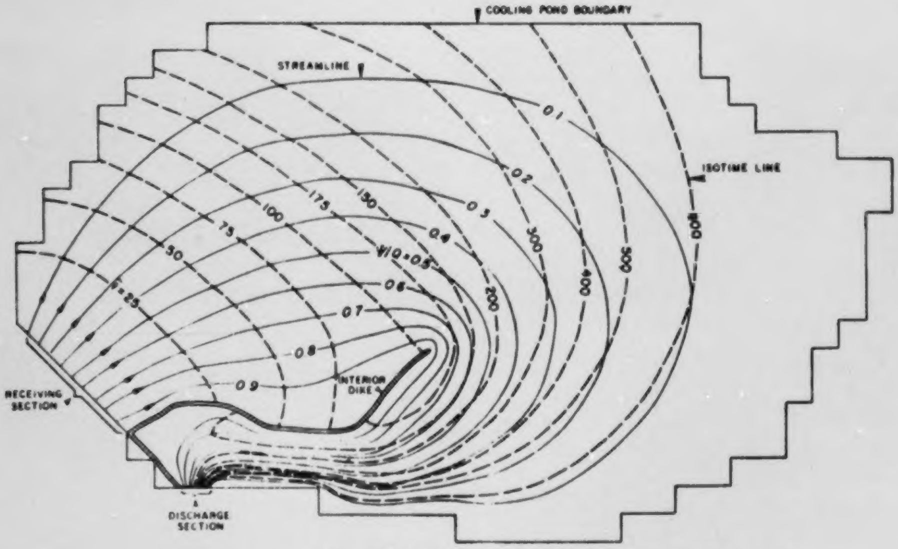
FIGURE 17. FINITE ELEMENT MODELLING OF HORSESHOE LAKE

3. Bottom friction forces are assumed to vary linearly with velocity.
4. Velocities are assumed to be realistically described by means of a stream function.
5. Water depths are assumed uniform.
6. The heated water can be considered to follow steady state flow streamlines.
7. The water is assumed to be subject to surface cooling with no longitudinal or lateral diffusion taking place.

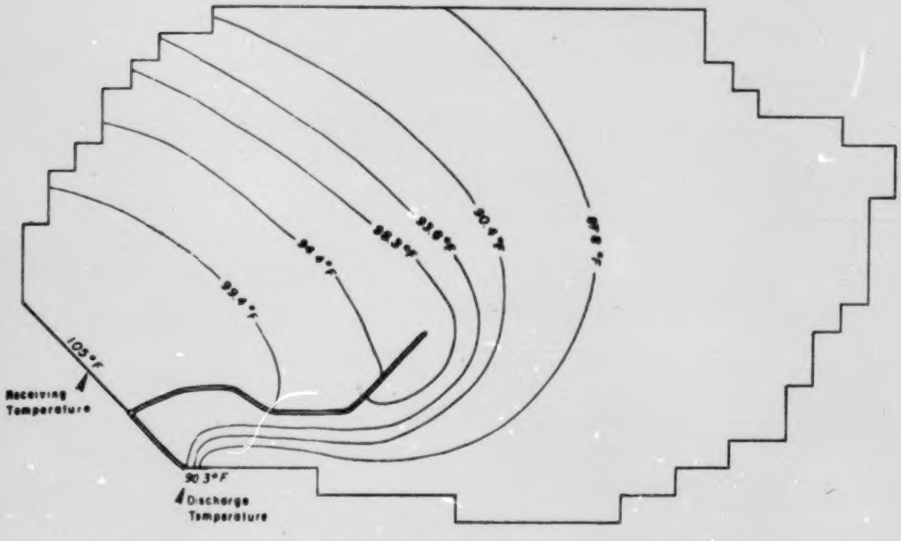
The governing hydrodynamic equations are simplified such that only terms expressing horizontal pressure gradients, surface wind stresses and bottom friction remain. The solution leads to the establishment of "isotime lines" akin to travel time along streamlines. There are instrumental in determining isothermal lines and the plant intake temperatures. Essentially, the solution technique involves following heated flows along pre-defined streamlines in the presence of surface cooling. Time ste in the order of hours can be used.

The model was applied to an open-cycle cooling pond in the southwestern United States. The pond was 7 feet deep and covered an area of 2700 acres. A mesh length of 500 feet was used in schematizing the pond for the explicit finite difference solution of the hydraulics. The results of the numerical solution of the hydraulics are shown in Figure 18a. Note the ability of the model to deal with an interior dyke. The model results compared well with single daily measurements of pond discharge temperatures taken over four days in August, 1972 (see Figure 18c). However, the observed data were less than adequate for model verification. Even less convincing is the unrealistically large lateral temperature gradients predicted near the pond discharge point as depicted in Figure 18b. This can be attributed to the neglect of diffusion and density effects.

3.5.4.3 Finite difference model by Edinger et al (1972). Edinger et al (1972) presented a finite difference model (HYETA), based on fully explicit solutions of both the hydrodynamics and temperature field. The major points of interest in this model are:

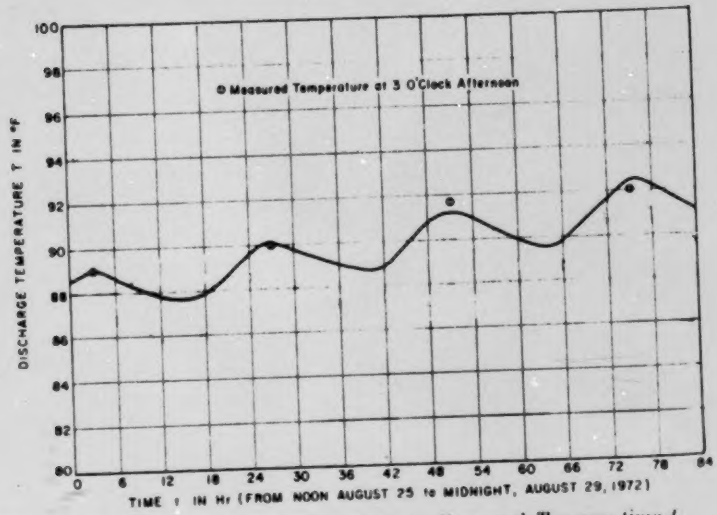


a. Flow pattern ψ/Q and isotime lines $\bar{I} = tQ/hL^2$ for the cooling pond.



b. Isothermal lines of the cooling pond at twelve noon, August 13, 1972.

FIGURE 18. FINITE DIFFERENCE MODELLING OF A COOLING POND



C. Discharge temperature of the cooling pond T versus time t.

FIGURE 18 (CONT'D).

1. The velocity field is determined from the time varying equations of continuity and momentum. The velocity field used in the temperature solution can be either time varying or essentially steady state.
2. The nonlinear convective acceleration terms are considered negligibly small and ignored.
3. The effects of wind shear and bottom drag on the velocity field are accounted for.
4. Variable depths throughout the water body can be considered.
5. Initial dilution of heat caused by so-called reverse flows can be modelled.
6. Horizontal heat diffusion in both principal directions is included.
7. Steady state meteorological conditions are assumed.
8. Evaporative water losses are given.

In order to solve the governing equations, the shape, bathymetry, boundary conditions, initial temperature field, diffusion coefficients and meteorological conditions associated with the water body must be known.

The treatment of hydrodynamics in this model was demonstrated by Reid and Bodine (1963) in their work on Galveston Bay. The hydrodynamic solution leads to the distribution of flow throughout a uniform finite difference grid system.

The capability of the model to account for variable pond geometry and particularly depth is most attractive, particularly when dealing with the irregularities which often exist in the shape of natural water bodies. These variations are important in determining the velocity field, which is in turn used in the solution of the heat transport equation.

The HYETA model was extensively tested in the frame of this study through comparisons with simple known solutions and with measurements. Some of these comparisons are presented in Appendix C in detail.

3.5.4.4 Discussion. A comparison of the three models has been summarized in Table 5. It illustrates that, with respect to the theoretical basis of the hydrodynamic solution, the treatment provided by the HYETA model is in general superior. Unlike other models, it is capable of not only representing irregularities in boundary shape with reasonable accuracy, but also accounts for variable bathymetry and wind stress. In addition, it possesses the ability to provide a transient hydrodynamic solution if required. Since the confidence one can place in a temperature analysis is limited by the confidence with which the velocity field is known, the superiority of the HYETA model in this respect is important.

Unlike the model developed by Yeh et al, both the other models consider diffusion of heat in solving the heat relation. The exclusion of this phenomenon can be significant, as demonstrated in section 3.5.4.2. Only the HYETA model includes an estimate of the evaporative water losses over time and considers initial dilution due to reverse flows. However, in its present form, it is also the only model to treat the surface transfer coefficient as a steady state parameter. This limits the application of the model to periods of time over which meteorological conditions can be considered essentially constant. However, only minor model modifications are needed to allow for the treatment of varied meteorology. Therefore, this limitation should not be considered a major handicap in future applications.

All three models have demonstrated the ability to reproduce actual measurements. All are currently operable and available for use. However, HYETA is at variance with the other models in that a listing of the source program has been published (Edinger et al 1972). HYETA is also the most attractive in terms of the overall practical implications of it limitations and assumptions. Therefore, it is recommended for general use in predicting detailed thermal regimes in shallow lakes and ponds. Appendix C provides further discussion of the model, including testing and calibration attempts accompanied by a source listing.

3.6 Economic Considerations for Cooling Ponds

The design and economics of a plant with an offstream cooling pond are as much site-dependent as they are a function of the plant design since weather conditions, land costs and construction costs influence the economics as clearly as does the cost of equipment. Because economic analysis of cooling pond construction and operation is well described elsewhere (Littleton Research and Engineering, 1970; Temple et al, 1974), it will only be touched on briefly in this section.

Based on the capital cost and operating expenditures for that equipment which is somewhat different in cooling pond designs, namely the condensers, cooling water pumps and turbines, Littleton (1970) developed a series of graphs and illustrated a procedure to give some insight into the economics of cooling pond design. Figure 19 for example, summarizes the cost of equipment for various land costs (including construction) and cooling pond temperature ranges (R). The economics of cooling ponds of various sizes are also compared in Figures 20 and 21 for several temperature rises through the condensers ($\Delta Tc = R$). Figure 20 applies to fully mixed ponds, and Figure 21 to plug flow ponds. These curves are based on average summer conditions (high back pressures) but can be modified for other climatic conditions and other land and construction costs. As we mentioned earlier, the optimum for a practical cooling pond would be somewhere between those for the mixed and plug flow cases.

Figures 20 and 21 also indicate a higher comparative cost for natural draft cooling towers. Similar figures, based on the land construction cost for small dams, can also be advanced to enable a comparison of onstream cooling ponds with the offstream ponds presented here. Unfortunately, these comparisons are not presently available in the literature.

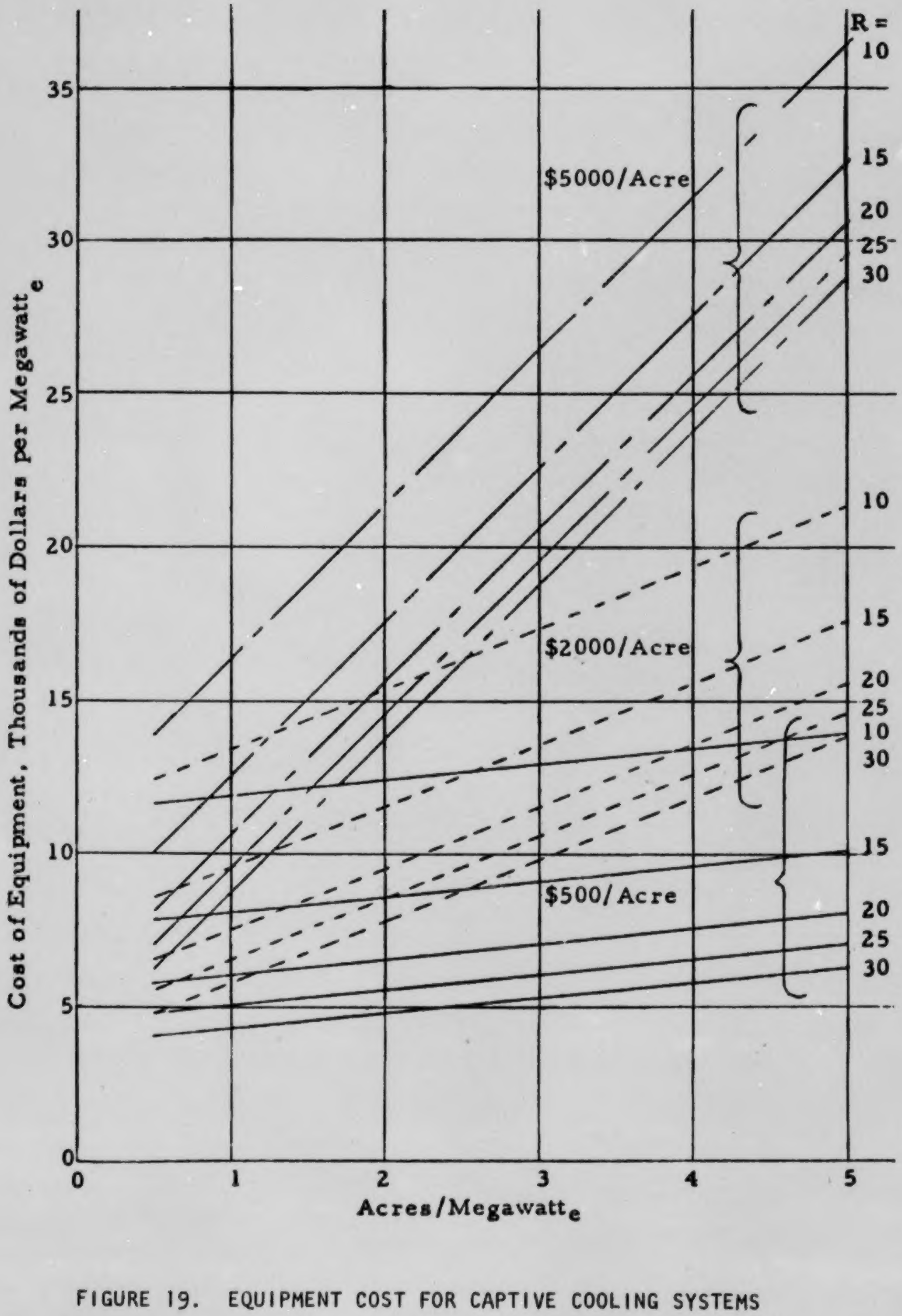


FIGURE 19. EQUIPMENT COST FOR CAPTIVE COOLING SYSTEMS

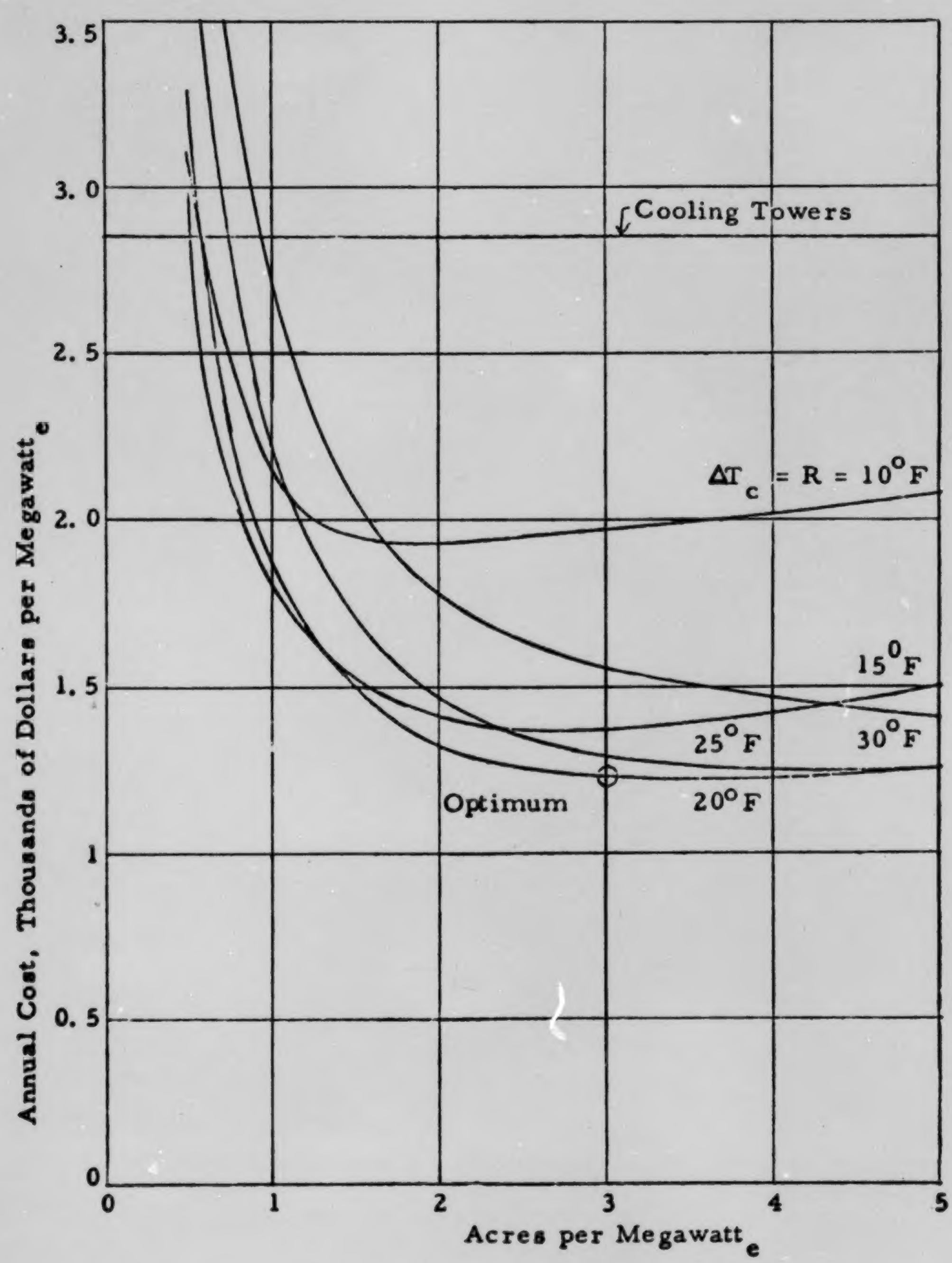


FIGURE 20. ANNUAL COOLING COST - MIXED POND. 2000 MW_e Plant
Land and Development Cost - $500 per Acre of Pond
Design Climatic Conditions for Philadelphia

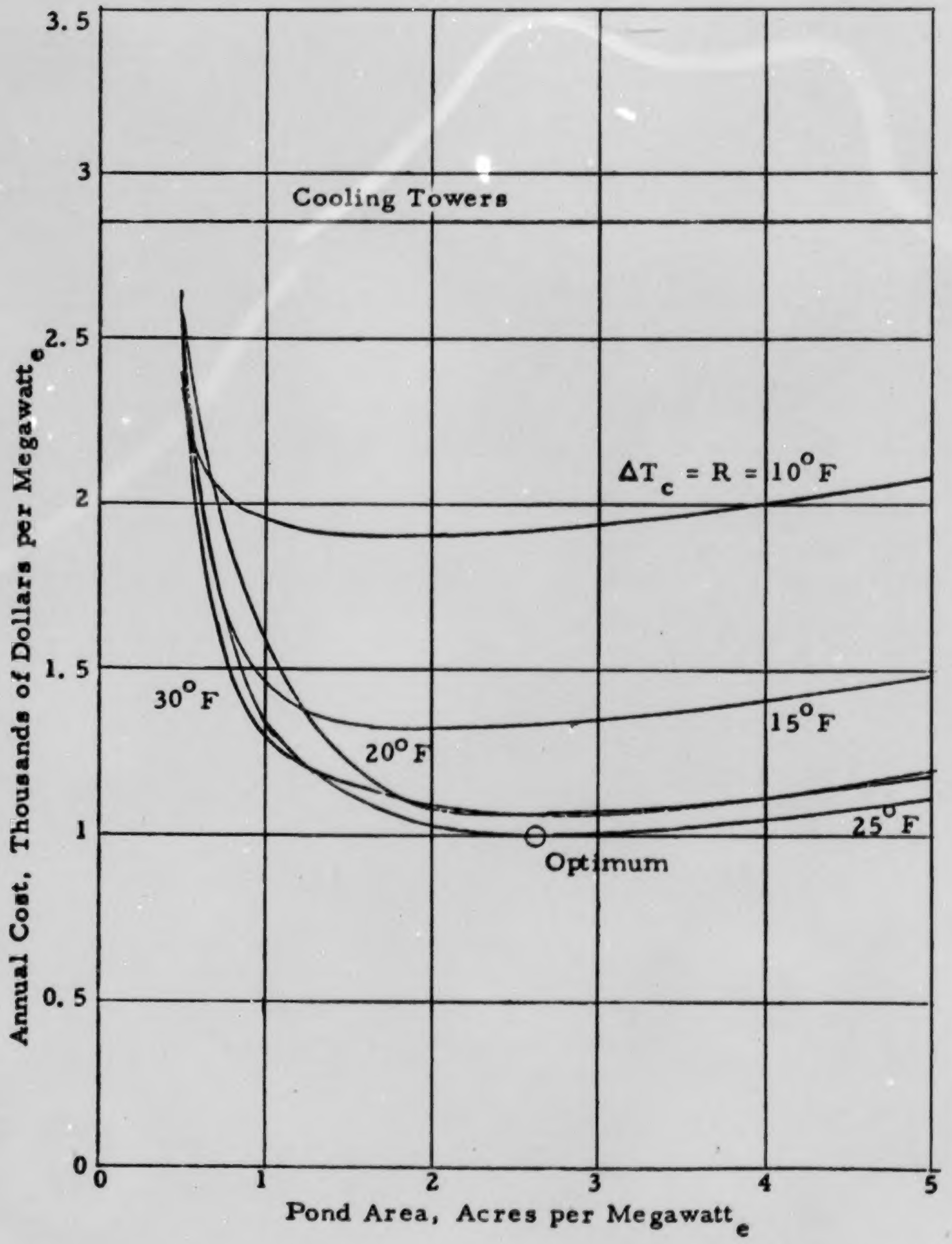


FIGURE 21. ANNUAL COOLING COST - PLUG FLOW POND. 2000 MW$_e$ Plant
Land and Development Cost - $500 per acre of Pond
Design Climatic Conditions for Philadelphia

4. HEATED DISCHARGE MANAGEMENT IN DEEP STRATIFIED LAKES AND RESERVOIRS

4.1 Introduction

Deep lakes and reservoirs will tend to undergo natural seasonal stratification and destratification. During winter, the lake or the reservoir will be cool, with temperatures varying from $0^{\circ}C$ at the surface to about $4^{\circ}C$ at the bottom. This situation will prevail until the end of winter. Heat is added at the surface in spring by solar radiation and this heat is transported to the lower layers by wind driven circulation and convection. Consequently, an isothermal situation will be observed during early spring. In late spring, the warmer surface waters progressively form a stable layer called the epilimnion and the water body becomes fully stratified. The latter situation prevails during the entire summer and, with the approach of fall, the eplimnion erodes into the hypolimnion. Finally, the balance between the epilimnion and hypolmnion becomes sufficiently unstable so that the remnant of the hypolmnion is entrained and the whole made homothermal. During the fall, the lake continues to be completely mixed until the onset of winter when rapid chilling of the surface is sufficient for ice to form.

While this important similarity exists between these two water bodies, deep reservoirs and lakes can be distinguished by other characteristics. In general, the physical features and thermal behaviour of a reservoir are influenced to a greater degree by the source river. In comparison to deep lakes, reservoirs often possess longer shorelines due in part to the presence of tributary side arms. Their surface area to volume ratio is largely dependent on the natural river gradient and valley formation; low ratios being associated with steep gradients and valleys, and high ratios resulting from the presence of broad valleys and significant tributary side arms.

In the presence of stratification, inflowing stream water seeks the level in the reservoir corresponding to its density. These densities are largely a function of water temperature. During spring, the temperature of inflowing river water exceeds that of subsurface reservoir water, causing the incoming flow to remain near the surface. In the summer and fall, when river water is typically cooler than the surface water in the reservoir, it will sink until it reaches the appropriate density level. these density underflows usually do not mix well and normally move through the water body with little mixing.

At variance with deep stratified lakes in which isotherms are observed to be essentially horizontal, isotherms in reservoirs tend to tilt in the downstream direction. This tilting is mostly attributed to the hydraulics of density underflows. Also contributing are large length-depth ratios in conjunction with the low residence times of reservoirs, as opposed to deep lakes.

In the case of deep lakes, the long residence times resulting from their great depth promote slow response to changing meteorological conditions. These residence times are of the order of nine months or greater. Also, the major source of cool water during the warmer months is from the depths of the lake where water cooled during the winter period is stored. In contrast, inflowing waters may represent a significant source of cool water in the case of a reservoir, although residence times may be as long as in deep stratified lakes.

As previously stated, the degree to which reservoirs differ from deep lakes is largely a function of the significance of the source river, especially in terms of residence time and water body shape. Consequently, the behaviour of many reservoirs is not unlike that of a natural deep lake.

4.2 Management Alternatives

In contrast to shallow lakes and ponds, it is possible to discharge to and withdraw cooling water from the hypolimnion of deep water bodies. The potential cooling alternatives are, therefore, the many combinations of deep, shallow, and intermediate depth intakes and outfalls.

The input of a thermal discharge and the extraction of condenser cooling water can affect both the hypolimnion and epilimnion. The epilimnion can be deepened and warmed by discharges to it and the hypolimnion can be depleted by pumping from it or discharging to it. In most cold lakes, the cold water biological species are the chief asset and the volume of hypolimnion is extremely important for maintenance of these species. In other lakes, there may be a requirement to protect both deep, cold water biota and warmer water biota in the shallow epilimnetic waters. Considering the full water body, the natural fall temperatures of a small lake can be extended by as much as a month by the additional waste heat stored in the system. The onset of stratification and spring warming will be advanced by a similar time increment.

The possibility of hypolimnion depletion is an important consideration with a bottom intake or outfall. The volume of natural lakes is usually quite constant and circulation patterns, inflow to the lake, stratification and potential for hypolimnion depletion are generally predictable. As long as the volume of hypolimnion water is not substantially reduced by pumping and cold water species can be maintained, a deep intake may be used. The deep intake is advantageous because it draws in warmer bottom water during the winter and eliminates intake icing problems. However, in those lakes that are highly productive in terms of organic matter, the hypolimnion intake water will be low in oxygen. Discharging this water without aeration or by rapid mixing may have a detrimental influence on biological populations in the plume area. In addition, there may be the problems of nutrient recirculation and nitrogen gas supersaturation, as mentioned earlier.

As with deep stratified lakes, the cool underflow in reservoirs can be depleted by pumping from it, the limit in many cases being the rate of underflow into the reservoir rather than a stored volume of hypolimnetic water.

A deep intake and partially submerged outfall can, however, be used to minimize the plume and attraction to the discharge area. A discharge to an intermediate depth will mix on all sides of the plume and will avoid warming of the surface layer and any subsequent increase in evaporation. The discharge can become stratified in an intermediate layer or will possibly become a sinking plume if the hypolimnion temperature plus the condenser rise is cooler than the epilimnion.

Measurements of the Marshal Steam Station serve to illustrate this point (Edinger et al, 1974). The winter thermal plume from the cooling water discharge floated on the top 5 feet of the lake, with entrainment from below being the main cooling mechanism. Excess surface temperatures were reduced to less than 2°C at distances of about one mile into the main body of the lake. In summer, because the cooling waters are drawn from the cooler hypolimnion, after passing through the condensers they are discharged at a lower temperature than that typical of the lake surface. Consequently, under calm conditions, the thermal plume tends to sink to a mid-lake level where entrainment occurs in three dimensions. Surface temperatures are slightly reduced in the vicinity of the plant due to mixing.

Also, at the Oconee Nuclear Station on Lake Keowee in South Carolina, a precast concrete skimmer wall has been constructed across the canal such that the large quantities of cooling water required will be drawn from the bottom of the lake. The temperature of the bottom waters is such that the condenser heat raises the temperature of the cooling water to that of surface waters under natural summer conditions. The cooling water is also discharged into a distant arm of the lake to reduce the potential for recirculation.

Consideration of a small intake flow volume and high condenser temperature rise combination may be required for hypolimnion preservation. If the lake is of sufficient size, a warm discharge pool on the surface that stratifies and exchanges heat with the remainder of the water body would not deplete the hypolimnion, but could lead to a significant evaporation loss from the epilimnion. Canal discharges that stratify in the channel may also be designed for some mixing and entrainment at intermediate depth. Again, however, tolerance levels may be exceeded and spawning activities reduced.

Recirculation by a surface discharge is also used as an alternative to keep the intake area free of ice. During the summer, however, deepening of the epilimnion may result from both the high velocity or low velocity surface discharge, although full warming of the epilimnion is principally related to high velocity discharge. This heating may result in increased production of warm water fauna with subsequent reduction in cold water species. In the winter, however, open ice-free areas can mean a source of oxygen to some shallower portions of the lake and prevent dissolved oxygen depletion, although this is not a problem in deep lakes.

The icing conditions in flow-through reservoirs are more closely related to those on rivers than on lakes (frazil). The best design is to recirculate only a portion of the heated discharge back into the intake forebay as it is usually impractical and difficult to control the recirculation of a large portion of the discharge. At multi-purpose thermal-hydroelectric dams, it is likely advantageous to directly recirculate a portion of the heated discharge to the forebay to prevent icing problems there as well.

Circulation of water in a reservoir is dependent on wind and the passage of water through the reservoir. A major effect of steam-electric stations is their influence on the circulation of water. If the major surface area and shoreline length of reservoirs is in the tributary arms, these bodies can be distinct and separate entities and are often used in pairs as an intake source and discharge point. This usually leads to increased circulation in the arms.

An upstream density wedge may be formed if the discharge is low velocity and released to sluggish backwater reaches (Edinger and Yanagida, 1972). These wedges may be sufficiently large to add significant warmed surface area. It may not be necessary to avoid these wedges, but in certain instances they may result in depletion of the dissolved oxygen beneath the wedge in the underflow.

Siting of outfalls in these usually sluggish river flows could also lead to a natural stratification as the discharge moves into the reservoir. As a consequence of such siting, a discharge which stratifies at the outfall point may mix vertically as it moves downstream. This will be accompanied by a decrease in temperature at the surface, with a corresponding increase in the bottom temperatures. On the other hand, as on the Cossa River in Georgia, a vertically mixed discharge can become more stratified and produce higher surface temperatures as it proceeds downstream.

As mentioned previously, the available tributary arms are often used as intake embayments or natural stratified discharge canals to the surface or intermediate depths. The depth depends on the relation between the condenser rise and the difference between the surface and bottom temperatures. If the condenser rise is greater than the difference, the discharge will remain on the surface. This arrangement, however, can lead to atmospheric nitrogen supersaturation.

Another design alternative is that of a submerged pipe or diffuser outfall. These enhance mixing rates and limit the surface temperature rise and associated evaporation. So as not to deplete the cooler flow through waters, however, the alternative with a low flow, high condenser temperature rise and a surface outfall may be advantageous (if the increase in evaporative losses is acceptable). In the instance that the tributary arms are used for surface discharge, it is usually desirable to put a weir on the lower end of the discharge canal to prevent fish from concentrating in the discharge canal. Such a device is most essential in the Canadian winter climate to prevent cold shock mortalities with winter shutdowns.

Another alternative is to place the steam station downstream of the dam. This is becoming a common practice in the United States and is used, for example, at the Cowens Ford Dam on Lake Norman and at the Muskeegan River plants. The intake can be taken from a cool low-water release and the discharge returned to the top of the reservoir. This leads, however, to expensive and difficult pumping problems and has probably been adopted to meet discharge standards requiring a cool plume. Again, the overriding disadvantage of this method lies in the biological impact resulting from atmospheric nitrogen supersaturation.

4.3 Examples of Canadian and American Practice

With the exception of the Great Lakes, the siting of thermal electric generating stations on small stratified lakes has not been a typical practice in Canada. The only Canadian station of any size in this category is the 100 MW Grand Lake Power Station in central New Brunswick. Grand Lake is approximately 24 miles long and 3 miles wide and reaches a maximum depth of 100 feet. However, near the station on the Northeast Arm, the lake is only 1.5 miles wide and the depth varies between 15 and 18 feet. At the immediate vicinity of the intake and outfall, the depth does not exceed 10 feet.

The Grand Lake plant is a combination of an older 15 MW unit (No. 1) and a more recent 85 MW unit (No. 2). Each unit has a separate intake but both intakes are designed as open channels and draw the condenser cooling water from the epilimnion. The intake/forebay canals are 250 feet long and 100 feet long for Units 1 and 2, respectively.

The outfall is also an open channel and is common to both generating units. The channel begins about 260 feet from the shore. At the shore, two jetties have recently been constructed to extend the outfall channel an additional 200 feet into the lake. The condenser temperature rise varies between 8.9°C and 10°C and the jetties were required to deflect the heated discharge further offshore and thus reduce recirculation back to the intake. Preliminary assessment of thermal effects for these and a number of other intake-outfall alternatives were included in an environmental study of coal-fired stations in New Brunswick (MacLaren Atlantic Limited, 1974). Aside from this study, however, a concentrated assessment of effects of this plant has not been undertaken. Essentially, as the lake does not function as a deep stratified water body for this plant, the results of similar studies should be viewed in the context of shallow lakes (see section 4.4.1).

There are several reservoirs in Canada used expressly to supply cooling water for large steam-electric stations. Two of these have a sufficient depth and inflow to exhibit stratification.

The oldest and largest of these is the Boundary Dam Reservoir on Long Creek near Estevan, Saskatchewan. The reservoir is about one-quarter of a mile wide, nine miles long, and 70 feet deep at the dam. The total reservoir volume is about 49,000 acre-feet, the surface area is 1500 acres, and the lake is well mixed by wind action.

The 882 MW Boundary Dam Station is immediately above the dam and uses once-through cooling with the condenser rise in the plant generally varying between 8.9°C and 11.1°C. The intake is also near the dam and is a submerged, open-ended pipe to a depth of about 35 feet. The condenser discharge is carried in a one and one-half mile long open channel to a point upstream of the intake. Although it was initially planned to discharge at the surface, the outfall is submerged to a depth of about 40 feet. Preoperational changes expected to result from the newest 300 MW unit were the subject of a three year study which was assisted by monitoring in the reservoir over its 20 year history.

This reservoir was created to provide cooling water for a thermal electric power generating station. Unfortunately, the Souris River, into which Long Creek drains, is the source of damaging floods. Consequently, there is also a need to use Boundary Reservoir for flood control purposes. Naturally, because of drawdowns, operation for flood control conflicts with use of the reservoir for cooling purposes, but the downstream peak flows in several recent floods in the basin have been significantly reduced.

The most recent cooling reservoir is presently being constructed for the 300 MW Poplar River Station near Coronach, Saskatchewan. The reserovir size and storage capacity will be eventually increased from an initial 400 acres (14,000 acre-feet) to 1200 acres (27,000 acre-feet) when the station reaches its proposed ultimate capacity of 1200 MW. Preliminary pond sizing has been based on a one acre/MW rule of thumb (Saskatchewan Power, 1974). The total reservoir length will be about six miles and the maximum depth will be about 60 feet. The intake structure will be near the dam and is designed as an open, submerged pipe to a depth of about 3 feet below minimum reservoir level and 36 feet below maximum level. The outfall for the first unit will follow a two-mile long open canal to a surface discharge slightly downstream of the intake. Additional units will also discharge through open canals, but these canals will release the cooling water at a point upstream of the intake.

In summary, the two Canadian reservoirs discussed above were initially constructed for cooling only and were not previously used for other purposes. The thermal stations on these reservoirs have submerged intakes at the downstream end of the reservoirs, and use low velocity shoreline discharges at the upstream end of the reservoirs. These design arrangements permit the reservoir to be used for surface cooling, and take advantage of stored hypolimnetic water or the cool water flow from upstream tributaries.

The Marshall Steam Station owned by the Duke Power Company is located on Lake Norman, North Carolina. The reservoir has a surface area of 32,500 acres and a volume of over 1 million acre-feet. Two 350 MW units are presently in operation with two 650 MW units under construction. During summer stratification of the lake (maximum depth 120 feet, mean depth 24 feet), the hypoliminial temperatures are 20-25°F cooler than those at the water surface (Gray and Stephenson, 1968). A submerged skimmer weir located 17 miles upstream from the station retains the colder bottom water, allowing the more oxygen rich upper layers to pass downstream. Cooling water is drawn under an inverted skimmer wall, from depths of 60-70 feet, located at the mouth of a small intake cove. Detention time in the intake canal has been estimated at 17 hours for the projected maximum cooling flow of 2,300 cfs. The discharge canal is 4,800 feet long, with surface area of 60 acres before merging with the main body of the lake. The minimum possible distance for recirculation is four miles.

The Keowee-Toxaway power generating complex in South Carolina is a multi-purpose power development consisting of an integrated combination of hydro-electric, reversible pumped storage and nuclear thermal systems (Heintz, 1975). The complex currently consists of three interacting components: Oconee Nuclear Station, Keowee Hydro Development and the Jocassee Dam reversible pump-turbine system. The combined generating capacity is presently rated at over 3,400 MW and is expected to eventually reach 17,000 MW. The Oconee Nuclear Station provides a base load of approximately 2,600 MW. The Keowee Hydro Station supplies peaking capacity, while the Jocassee Station provides intermediate capacity energy. The Oconee and Keowee Stations are centred on the largest reservoir of the development, Lake Keowee. This is a 18,500 acre reservoir formed by the damming of two watersheds and interconnected by a 2,000 foot canal. This water body provides heat and storage for hydro-electric generation as well as a source of cooling water for the nuclear steam plant. The proximity of the two stations eliminated the need for including emergency diesel powered generating units in the nuclear plant design. Cooling water flow required for the nuclear station is in excess of 4,500 cfs. It is drawn from the bottom of the reservoir and discharged at some distance from the intake location, thereby creating little potential for short circuiting. The temperature of the bottom waters are such that the addition of waste heat from the plant causes the cooling water to return to the lake surface near naturally occurring summer surface temperatures. Two additional thermal plants, also employing once-through cooling systems, are to be located on the lake in the future, bringing the total thermal generating capacity to

7,000 MW. The Jocassee development is based on a reversible system of hydro generation and pumped storage. Conventional hydro power is generated by drawing down Lake Jocassee, while at other times water is pumped from the lower pool, Lake Keowee, to Lake Jocassee for subsequent use in hydro generation. Eventually, more high-heat pumped-storage developments are to be constructed using Lake Jocassee as their lower pool. In addition to their use in the production of electricity, the reservoirs have provided a number of complimentary services: improvement of downstream water quality, recreation, municipal water supply and flood control.

4.4 Biological Considerations

A knowledge of the general biological characteristics of a stratified water body will give some insight into the safeguards required and, consequently, the particular mode and design of the cooling system. For example, coldwater fish will likely be residents of the water body, particularly if it is natural (i.e. a lake as compared to a reservoir). These fish may include salmonids and coregonids. Temperatures required for spawning for these fish are low and the spawning grounds or access routes to spawning grounds must not be affected by thermal plumes. Whitefish and lake trout, for example, spawn in rocky, gravel-bottom areas in bays within the lake itself, while the other trout species will migrate to feeder streams to spawn (Scott and Crossman, 1973). The necessity of maintaining spawning grounds relates to maintaining adequate natural populations of those fishes; the importance of those fishes for sport or commercial exploitation needs no further mention.

Most of the primary productivity in a stratified body will take place in littoral (shoreline) areas and in the epilmnion. Rooted macrophytes and the periphyton are the producers in the littoral zone, while phytoplankton provide the primary productivity in the epilimnion. These organisms, in addition to secondary producers such as benthic organisms, provide food for forage fish which themselves become food for game fish.

While dissolved oxygen levels may become low in the hypolimnion, especially just before turnover, DO levels in the epilimnion are normally high due to air-water exchange and vary diurnally due to photosynthesis by plankton.

It is possible that the activities at a power plant might cause destratification (e.g. jet release of heated discharge into the hypolimnion) or a lowering of primary productivity and total oxygen levels in the lake (e.g. withdrawl of epilimnetic water leading to the destruction of phytoplankton through entrainment).

4.4.1 Heated discharges

In rare cases, it may be extremely beneficial to promote some mixing of hypolimnetic and epilimnetic waters in order to control algal blooms (a symptom of eutrophication) in the epilimnion or to maintain adequate oxygen levels in the hypolimnion in order to prevent (salmonid) fish kills. In this particular alternative, it might be advantageous to withdraw from the epilimnion with the expectation of destroying certain algae, particularly Cyanophyta, by discharging through a multiport diffuser located in the hypolimnion. Destratification in reservoirs by means of bubbling air from the hypolimnion is practised at Parvis Lake, Colorado to alleviate the problem of epilimnetic algal blooms and hypolimnetic deoxygenation (Lackey, 1973) and in the Puddingstone Reservoir, California, to maintain adequate hypolimnetic oxygen (Fast and Amant, 1971).

Artificial mixing is, however, undesirable in most cases in that the destruction of the thermal stratification may raise temperatures in the entire water body to a level inhospitable for cold water fish. Such an effect has been noted when a reservoir was destratified at night using air (Fast and Amant, 1971) and, in that case, a further thermal input into the hypolimnion from a power plant might cause more problems than it solves.

A general rule of thumb for the particular mode or design of a cooling system to be used in a stratified water body is to try to maintain the populations of any cold water fish species that reside in the lake and to maintain operations so that the process of eutrophication is not accelerated. Algal blooms, particularly those involving Cyanophyta, may be stimulated when the influx of heated water from a power facility raises the final water temperature to $30^{\circ}C$ or more. If this rule of thumb is followed, then the general biotic integrity of the stratified water body will be maintained.

There have been some studies carried out to determine the effect of a power plant operation on certain reservoirs. At Lake Norman, North Carolina, with a maximum depth of 37 metres, the Marshal Station discharges hot water at an average ΔT of 9.1°C. It was found that a variation in phytoplankton existed at different points in the lake. The difference in populations among the various sampling points was thought to be due to natural variations and not to thermal effects brought about by the plant. Furthermore, no alteration of primary productivity can be attributed to the effects of heat (Jensen and Geyer, 1971). Jensen and Geyer (1971), however, found that periphyton productivity as measured on artificial substrates was increased in the region of the discharge canal compared to the intake area. The lake was found to support a good warm water sport fishery for largemouth bass, white bass and crappies. Threadfin, carp, shad, gar and catfish were also common (Jensen, et al, 1974). Spawning was not impaired by the thermal plume; in fact, fish were observed to spawn in the discharge canal and to move into the discharge canal in winter months. The spawning period was advanced in the discharge canal compared to areas at ambient temperatures (Jensen and Geyer, 1971). Normally, these species spawn when water temperatures are typical for spring and summer.

At the Grand Lake Plant in New Brunswick, benthic invertebrates and fish were studied by the New Brunswick Department of Fisheries and Environment (1973). The plant is located at a shallow end of the lake (Newcastle Bay) near the inflow of Newcastle Creek, and only that shallow area is affected by the plant. The lake itself has a maximum depth of 100 feet and is not well stratified. The plant produces 100 MWe at a ΔT max. of 10°C. Benthic fauna were found to be more diverse near the discharge than in the intake area. Diversity and number of organisms decreased with increasing distance from the plant. Organisms present included amphipods, and the larvae of mayflies, dragonflies and dipternas, as well as worms, clams and snails. Fish species common in Grand Lake include white perch, gaspereau, Atlantic salmon, whitefish, yellow perch, suckers, shiners, pickerel, American eel, pumpkinseed and smelt. No negative effects on those fish species attributable to the thermal effluent from the plant were observed.

As discussed elsewhere, the effects of heat in Grand Lake cannot be separated from effects of chemicals in the water. Water quality in Newcastle Bay, including the area where the power plant discharges its effluent, is poor with pH ranging to below 6.5 and ash, coal and coke fines being present in the water. That the power plant does not evoke a negative effect even in the immediate vicinity of the outfall is probably due to the poor ambient water quality. In fact, because of the complexity of the situation, no definitive conclusions can be drawn.

Thus, the impact of a thermal discharge on the aquatic environment depends on the location and design of the intake and discharge structures.

However, the surface intake and surface discharge mode is probably the preferred one for the Canadian condition for the following reasons:

1. The hypolimnion is not heated and stratification is, in fact, reinforced.
2. Nitrogen gas supersaturation heated water discharged from the plant will not occur as it will with deep intake - surface discharge.
3. Areas of open (ice-free) water will be maintained for longer periods in the year. This leads to longer exposure to the atmosphere and, therefore, prolonged aeration and less likelihood of under-ice oxygen depletion.

A drawback that may result from stabilization of the epilimnion, however, is that mixing of epilimnetic and hypolimnetic water due to turbulent wind-generated effects may be inhibited. This may lead to oxygen depletion in the hypolimnion before the fall turnover.

Deep water intake and surface discharge results in lower surface temperatures, but the mixing of the two layers (i.e. depletion of hypolimnion) may be ecologically detrimental for several reasons:

1. Recirculation of nutrients from the hypolimnion to the epilimnion will lead to increased algal growth and will, in fact, speed up the eutrophication of the lake.

2. Loss of cold water from the hypolimnion will result in the elimination of cold water sterothermic species.
3. Supersaturation of heated water with nitrogen will result from this intake-outfall mode. Such nitrogen supersaturation will lead to gas-bubble disease in fish, particularly if the outfall is of the "canal" type, allowing a population of fish to reside there.

One benefit which will result from this mode is that, because of the epilimnion-hypolimnion mixing, the deeper waters of the lake will be less likely to be depleted of oxygen. If oxygen depletion of the hypolimnion is a serious problem in the particular water body in question in the natural circumstance, and providing that the hypolimnion is never depleted throughout the year by the activities of the proposed plant, a deep-intake surface outfall could be considered.

Deep water intake and deep water discharge minimizes both surface temperatures and vertical water circulation. However, since heat dissipation to the atmosphere is small compared to the other modes, most of the plant waste heat ends up as stored heat in the deeper layers of the lake. This will, of course, lead to an appreciable rise in the average temperature of the lake and unless the result is specifically desired, (e.g. for warm water fish culture) it is not recommended.

4.4.2 Reservoir monitoring program

Stratification in reservoirs is caused by density (temperature) differences between the inflow and the impounded water. Typically, the colder water flowing into the reservoir is subjected to underflow on its way through the reservoir. With a residence time much lower than that for a true stratified lake, the hypolimnetic water in a flow-through reservoir is not so likely to become depleted of dissolved oxygen, and chemical stratification will not likely occur. A biological monitoring program would be necessary in order to formulate designs and operational practices for the cooling system of a thermal power plant to be situated on the reservoir. A reservoir is often multipurpose, being used for hydroelectric developments, flood control, municipal or industrial water sources, and recreation.

In order that the "recreation" facility of the reservoir and the water quality and biological quality of the reservoir and of the river downstream from the reservoir be maintained, an assessment of the biological characteristics of the reservoir, feeder streams and downstream flow must be made. Data of a qualitative and quantitative nature must be obtained. For example, if the reservoir is to be maintained for recreation, then any cold water fish (e.g. trout) present in the water body that are an important recreational resource must not be endangered, nor must access to suitable spawning areas either in the reservoir or in feeder streams. Excessive algal blooms or macrophyte growths become a great nuisance when the reservoir is to be used for recreational purposes or as a water source. The operation of the power plant should not enhance algal blooms or the growth of aquatic macrophytes as has happened at Lake Wabamun, Alberta (Reid, Crowther et al, 1973)

Although it is mandatory to design the ecological surveillance program to fit the unique characteristics of each potential site on any reservoir, there are certain activities which should be included in each program. These are: a) a preoperational ecological background site study; b) a comparable post-operational survey which should be carried out periodically after the plant goes into operation and should be carried out before and after the construction of any additional units added to increase capacity; c) a series of predictive bioassays, models and simulation systems; and, d) a continuously operating biological monitoring system.

Briefly, a program to provide scientifically sound data on the effects of the operation of a thermal generating station on the aquatic community of a reservoir and the downstream communities should be designed to show whether or not the following requirements are being met at that particular site: a) heated wastewater discharges are not detrimentally altering the productivity characteristic of that particular reservoir; b) temperatures are not exceeding either the maximum or minimum tolerances for indigenous organisms; c) fish and other aquatic organisms are not being acclimated to temperatures so high that they would die from low temperature stress if the plant were to cease functioning in midwinter; d) temperature variations do not preclude specific seasonal activities such as production and maturation of reproductive materials, produce aberrant behaviour, or in other ways upset seasonal cycles; e) temperatures permit the maintenance of the species diversity characteristic of that particular local; and, f) temperatures do not impede the downstream drift of insects, the migration of fishes, or other activities of this type. These represent the major parameters that should be considered at all plant sites. However, almost every site is going to have additional requirements which do not exist at all other sites. For example, at sites in the far north one might be required to determine the effects of melting the ice which permits over-wintering of water fowl in areas where they would not normally over-winter.

Generally, the parameters that need to be measured in a reservoir are not qualitatively different from those that should be evaluated for any other water bodies, but the emphasis placed on any particular parameter (e.g. fish) will depend on the particular location and uses of the reservoir.

A monitoring program designed to provide data from which the impact of the plant can be charted must include a census of the fish species present, giving relative abundance, if possible, and an assessment of the standing crop and species types of aquatic vegetation, phytoplankton and phytobenthos as well as zooplankton and zoobenthos.

Power plants are often situated on an arm of the reservoir and the discharge of heated water typically causes the entire water mass of that arm to become significantly warmed. The overall population of a fish species present in the reservoir will not be endangered by this heating unless the major spawning area for that species is located in the particular arm in question. Hence, the fish populations must be known, as must the life histories and spawning requirements of the various species. Biota in littoral zones and benthic areas in the heated arm of a reservoir are most likely to be affected by thermal discharge, the plankton and nekton being only transient residents of the area. Consequently, the shoreline and bottom areas must be most closely monitored. Rooted aquatic plants, their epiphytes, and organisms residing on or in the bottom mud or sand cannot escape if they are entrained by heated water. Unless they can adapt to the new environment, they will be replaced by those heat-tolerant "opportunistic" species that can readily adapt to changing conditions. Shifts in species composition and numbers can be expected to result from the discharge of heated water into the reservoir. If this shift or change from the natural preoperational condition presents a situation which is qualitatively deleterious, then by means of the monitoring program, the rate of change of the biological condition of the reservoir can be estimated. A value judgment must then be made regarding a comparison of the various valuable qualities in the reservoir that will be lost and the cost of remedial action for the plant cooling system.

Further particular details involved in monitoring individual biological parameters have been reviewed in many texts, e.g. Battelle Source Book for Monitoring Methods (1971); therefore, only the concepts have been outlined here.

4.5 Hydrothermal Modelling

A generalized approach for temperature prediction in deep lakes and reservoirs is difficult because of the complex interaction between geometry, inflows, outflows, wind driven circulation, wave action and the variation in meteorological conditions. No two water bodies behave in the same manner and each has to be dealt with according to its particular properties. Studies carried out by Sundaram et al (1969), Huber and Harleman (1968), Anderson (1954), and Orlob and Selna (1970) may be considered to represent classical situations.

Hydrothermal modelling of the behaviour of heated discharges in deep lakes and reservoirs is an extension of the modelling work developed for describing natural conditions. There are many analytical and numerical models available for modelling of temperature in natural conditions. A clear understanding of the natural behaviour of the water bodies is necessary before the application of a time varying thermal model is attempted. Simple analytical models provide quick estimation of the natural behaviour and response to thermal discharges and should be used in the initial analysis.

4.5.1 Analytical models

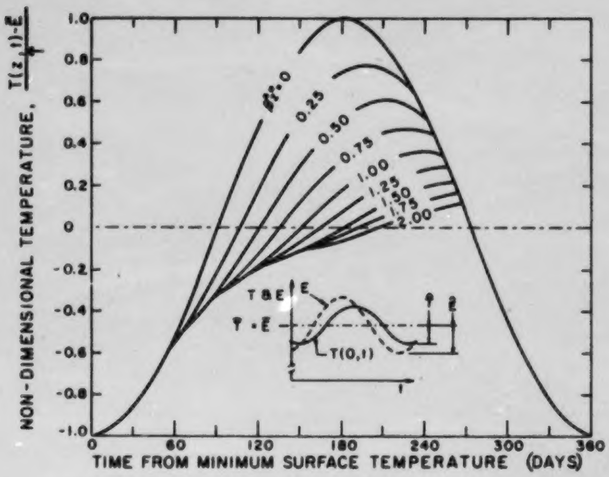
Analytical models normally have very simplifying assumptions in order to obtain viable solutions or approximations to actual temperature variations. Analytical models may be considered in any hydrothermal modelling before using complicated numerical models in a particular case because preliminary results from analytical models will give an indication of the applicability of the numercial models and the validity to any assumptions involved. Simple analytical models for deep lakes and reservoirs are one-dimensional models in which the temperature is assumed to vary in the vertical direction only.

The basic heat balance equation for these bodies which defines the heat transport process is a planar homogeneous equation in which a balance is maintained between vertical advection, diffusion and the time rate of change of heat. Solar radiation and any other heat source is considered to be absorbed at the surface. In some representations, it is also possible to include solar radiation penetration and heat sources within the water body.

Thermal analysis of lakes and reservoirs is also a time-dependent problem because of the continuously varying input of solar radiation, the time-varying rates of surface heat exchange and the vertical advective fluxes. The vertical advective flow is determined completely once the vertical distribution of inflows and outflows is specified.

A simplified, analytical, seasonal heat balance based on planar homogeneous balance equations for the case of no vertical advection has been presented by Edinger (1970). It is useful for first-order estimates of stratification when field data are limited, and for comparison with numerical solutions of more complex problems. The solution is based on periodic variation of temperature with its amplitude decaying with depth. A relation of the temperature amplitude and phase to the equilibrium temperature is also given. An example of the expected variation in temperature at different depths is compared to these same parameters for equilibrium temperature in Figure 22.

Thibodeaux (1975) presented an analytical method based on the semi-infinite solid model. The stratified water body is treated as having infinite depth with no vertical flow taking place. No heat absorption beneath the water surface is considered. For this situation, the temperature variation is easily represented by the solutions of classical heat conduction equations. The simulated temperature of Beaver Reservoir in Northwest Arkansas compared very well with the field measurements which are shown in Figure 23a.



Seasonal Changes in Dimensionless Vertical Temperature Structure for a Solar Heated Lake. Based on Edinger 1970.

Parameters of Depth Decay, Time Lag, and Temperature Amplitude Ratio, for Seasonal Cycle of Vertical Temperature Structure

Vertical Diffusivity, D_z (m^2/day)	Depth Decay, β^* (m^{-1})	Coefficient of Surface Heat Exchange, K (Wm^{-2} C^{-1})	Time Lag τ_0 (days)	Amplitude Ratio ($\hat{T}/\hat{E}$)
2.32	0.060	30	11	0.80
		35	9	0.83
		40	8	0.85
		47	7	0.87
4.60	0.043	30	14	0.73
		35	12	0.77
		40	11	0.80
		47	10	0.82
9.30	0.030	30	18	0.62
		35	16	0.70
		40	14	0.73
		47	13	0.76
18.60	0.020	30	22	0.56
		35	20	0.62
		40	18	0.64
		47	16	0.68

FIGURE 22. SEASONAL CHANGES IN DIMENSIONLESS VERTICAL TEMPERATURE STRUCTURE FOR A SOLAR HEATED LAKE

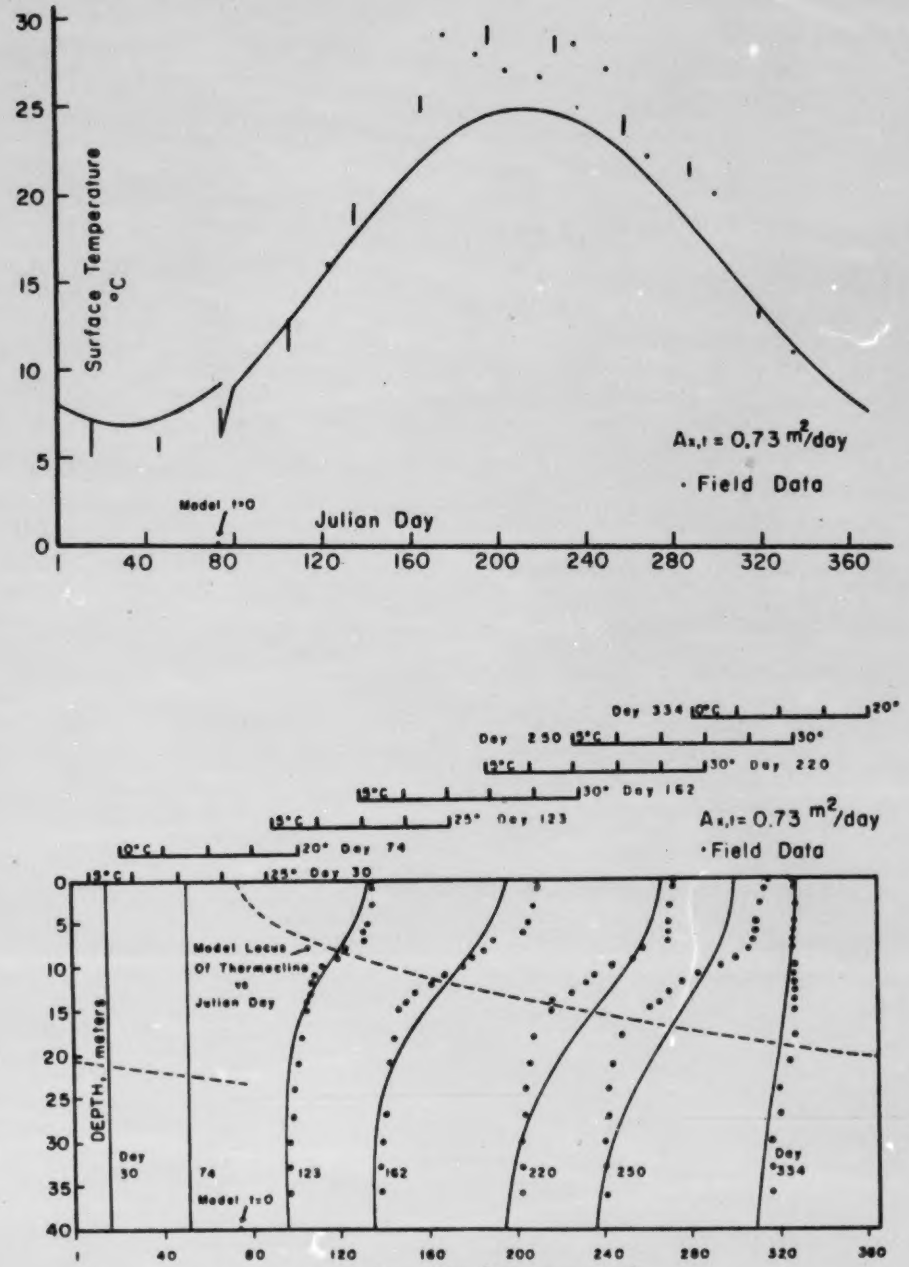


FIGURE 23a. SEMI-INFINITE SLAB MODEL, SIMULATION TEMPERATURE IN BEAVER RESERVOIR

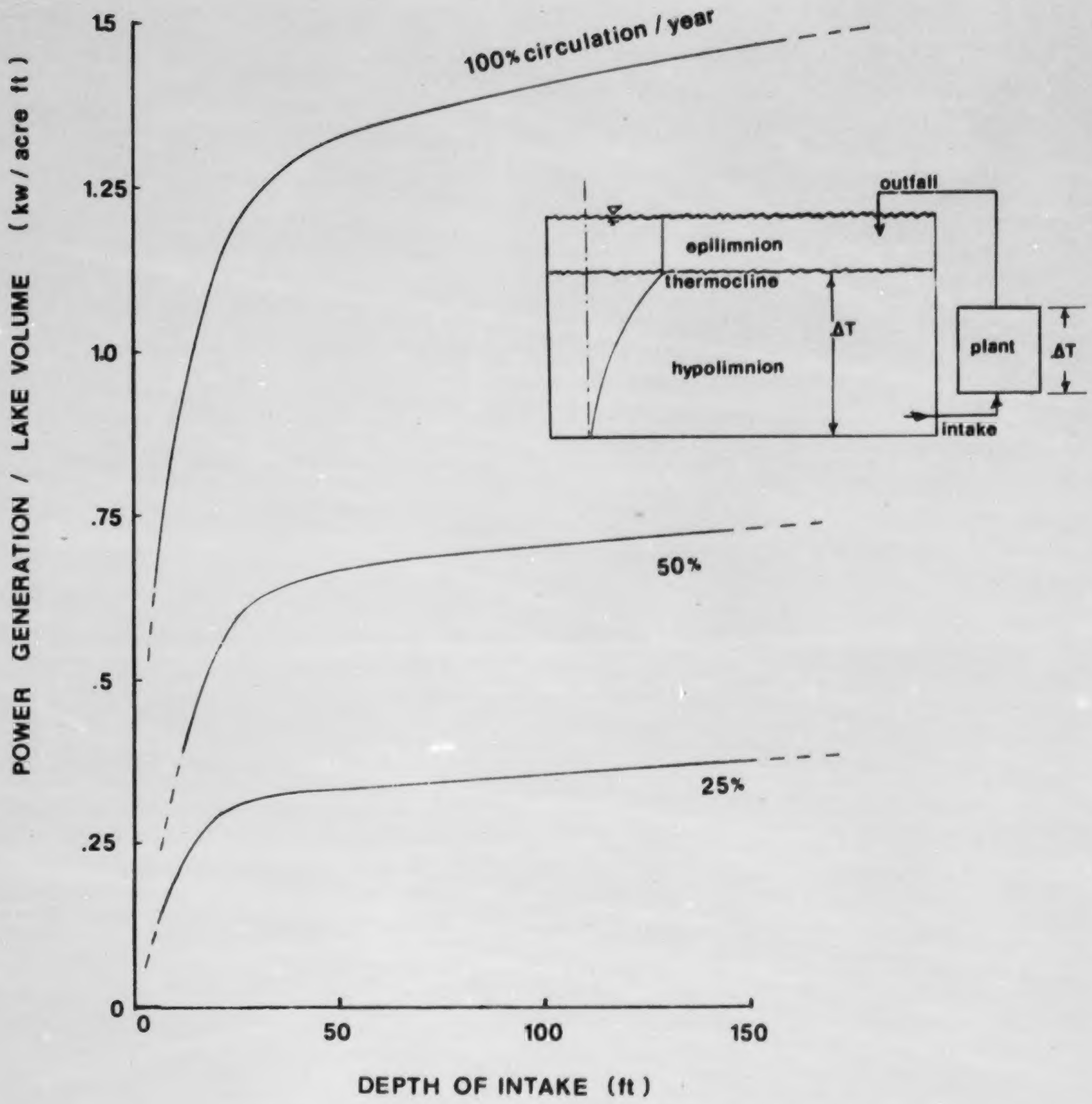


FIGURE 23b. PERCENTAGE OF TOTAL LAKE VOLUME PUMPED BY A PLANT PER YEAR

Rahmn and Marcotte (1974) presented an analytical method to predict thermal stratification in large bodies of water such as deep lakes and reservoirs. The method assumes two distinct horizontal layers in the water body. The surface layer is considered well mixed and the lower layer is the diffusion layer in which the temperature varies from top to bottom. Though the approach to the solution is analytical, the differential equations are integrated using a numerical scheme. The computed results compared very well with measurements obtained in summer months for Chaleur Bay, New Burnswick, but the model has not been used to date for a small water body.

An analytical model which takes into account vertical advection due to withdrawal flows and a variation in the cross-sectional area was developed in a study of Sherbrooke Lake in Nova Scotia (MacLaren Atlantic Limited, 1975) by extending the "no advection" analysis given by Edinger (1970). The area of cross-section of the lake is represented in an exponential form and the vertical advection is included as a mean velocity using the rate of flow and an average area of cross-section. The solution is again represented in a periodic variation with the amplitude decaying with depth, and takes the form:

$$T(Z,t) = \overline{T} - T_1 \, [\cos(wt - \alpha Z)] \, e^{-\beta Z} \qquad (1)$$

in which: Z is the depth from surface, $\overline{T}$ is the mean annual surface temperature, T_1 is half the annual amplitude of surface temperature, w is the annual frequency, and α, β are decay parameters which vary with depth. When the value of vertical flow approaches zero and the cross-sectional area becomes constant, the solution reduces to the form of the no advection case.

This approach is used in the following example in which the cold water present in the hypolimnion of a stratified lake is used as the coolant for a power plant. The following assumptions are made:

i) Cold water is withdrawn from the hypolimnion and discharged into the epilimnion.

ii) The temperature rise across the condenser is equivalent to the temperature difference between the surface and bottom layer, i.e. water is discharged to the surface at the surface temperature. (The system is schematically shown in the inset sketch in Figure 23b).

iii) The lake has a uniform cross-sectional area.

Now, assuming different withdrawal rates over the summer period, the power plant capacity can be calculated for different intake depths in the hypolimnion.

Figure 23b illustrates the relation between the cooling water withdrawal rate and depth, and the power to lake volume ratio (KW/acre-feet). A cooling water flow with 100% circulation per year implies that in one year the total volume of water passed through the condensers would equal the mean lake volume. The approach can be easily modified to consider circulation for the time periods when stratification is present.

4.5.2 Analytical consideration of density underflow

Density underflow usually occurs in flow-through reservoirs, which are an intermediate case between the stratified lake and the river. Many of the properties of stratified lakes are applicable in the case of flow-through reservoirs. However, the relatively large flow through the reservoir, and the increased surface area and shoreline length, demand a different approach to temperature prediction. Tilted isotherms will be observed in this case, as opposed to horizontal isotherms in lakes. Depending upon the temperature of inflow waters, artificial stratification patterns can be superimposed on the variations due to natural conditions. Prediction of temperature in these cases is dealt with later in this section. In the case of a series of impoundments situated fairly close to one another over a stretch of river, cool water released from one impoundment will enter the downstream impoundment as a density underflow. Warming of the cold water releases due to surface heat exchange can take place only in that reach of reservoir between the upstream dam and the duck-under point of the density flow. Incorporating all of the heating and cooling mechanisms into a comprehensive temperature prediction scheme is difficult because many of the mechanisms of stratified flow hydraulics through impoundments remain unknown.

The thermal structure of flow-through reservoirs can be investigated analytically to some extent by the models described in section 4.5.1. However, in the case of large cool water flows from upstream points, an artificial hypolimnion is formed creating an epilimnetic wedge. This process is schematically shown in Figure 24a. An appreciation of the formation of this epilimnetic wedge will be useful in the formulation of an analytical model.

Although the above time-varying analytical models are themselves most useful in the preliminary screening of alternatives, preliminary simulations should be carried out with and without the addition of heated discharges. The difference between the two results will give an indication of the thermal changes to be expected in the water body.

4.5.3 Numerical models

4.5.3.1 One-dimensional models. For thermally-stratified deep lakes and reservoirs, a large number of one-dimensional computer models are available for the prediction of the thermal structure. One-dimensional models for deep lakes and reservoirs represent the complicated thermal and flow fields in a highly simplified manner. The basic heat transport equation used in all one-dimensional models is the planar homogeneous heat balance. There is a loss of resolution and accuracy inherent in the application of a one-dimensional schematization to any reservoir or deep lake. (A one-dimensional schematization is presented in Figure 24b.) Temperature isotherms are simulated as strictly horizontal and complex flow patterns are reduced to simplified representations. Additional empirical assumptions are needed to handle processes that are explicitly solved in a two-dimensional model.

The WRE (U.S. Corps of Engineers, 1973; Water Resources Engineers, 1969) and M.I.T. (Huber and Harleman, 1968) reservoir models are examples of the one-dimensional representation.

The M.I.T. model was developed for the prediction of the vertical temperature profile in a deep lake or a reservoir. Inflows and outflows are taken into consideration, but the model provides for only one inlet and one outlet. The velocity profiles of the inflow and outflows are represented by a Gaussian distribution. This model assumes the inflow

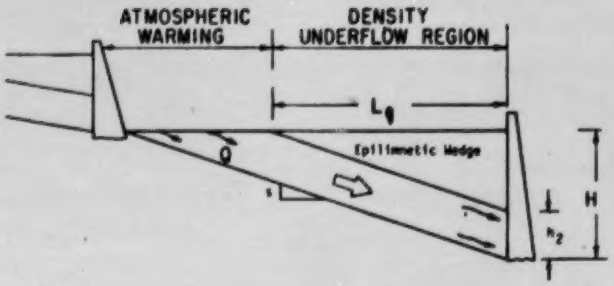


FIGURE 24a. DEFINITION SKETCH FOR SIMPLIFIED DENSITY FLOW COMPUTATION FOR A RUN-OF-RIVER RESERVOIR.

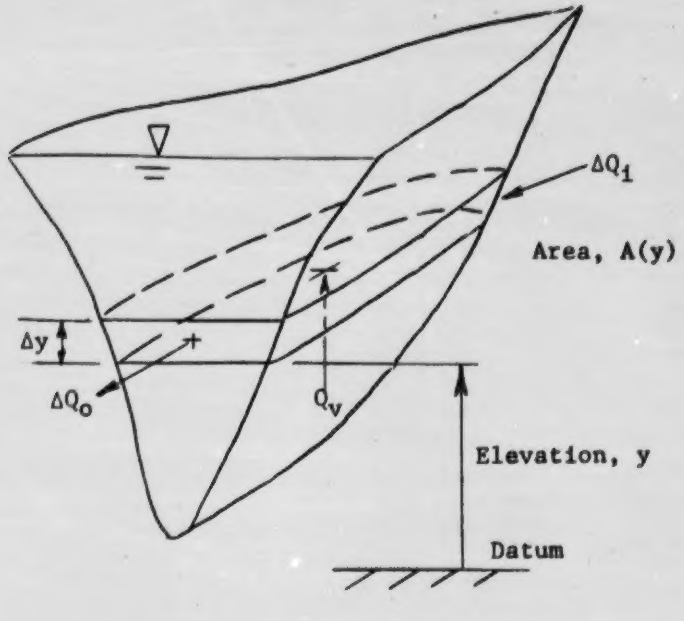


FIGURE 24b. RESERVOIR AND ONE-DIMENSIONAL SCHEMATIZATION

is mixed with the surface waters. The resulting temperature of the inflowing water will then be an average of the river inflow temperature and the temperature of the water mixed with the inflow. This resulting temperature is taken from the surface and then introduced at a level at which the water has a similar density. Thermal discharges can be considered by specifying the heated discharge temperatures to the inflow. In case of a deep lake where there is no inflow river system, the only inflow will be discharge from the power plant. However, with conventional outfalls, and with different outfall structures as well, the temperature distributions near the outfall cannot be simulated with this model because the uniform spread of a thermal discharge over a horizontal plane is obviously an over-simplification of the actual process. Further, the use of the model for reservoirs with surface ice cover has not been documented. However, the results of the model compared very well with data obtained from the Fontana reservoir. Figure 25 shows comparisons between the predicted and measured values of the natural temperature variation. The predictions are in reasonable agreement with the measured values.

The computer program and a good documentation is available in Huber and Harleman (1968). Extensive use of this model for heated discharge studies has not been described in the literature. Since this model accounts for one inflow only, it will be directly applicable only to lakes where the inflow is the heated discharge. However, in reservoir situations where there is a supplementary river flow, the problem can be solved by mixing the river flow with the heated discharge to result in a single inflow to the reservoir.

The WRE model is a quasi two-dimensional model in which the reservoir is longitudinally divided into one or more segments. Each segment is represented as a set of horizontal layers within which the one-dimensional assumption applies. The segments are linked by interflows which are the only mode of heat transport in the horizontal direction. These interflows are confined between specific elevations which are calculated in the program.

In the WRE model, inflow and outflow velocity profiles are represented by a uniform profile. Surface heat exchange is calculated from the individual components using meteorological data. Provision is made for computations with ice cover. Any time step can be used in the

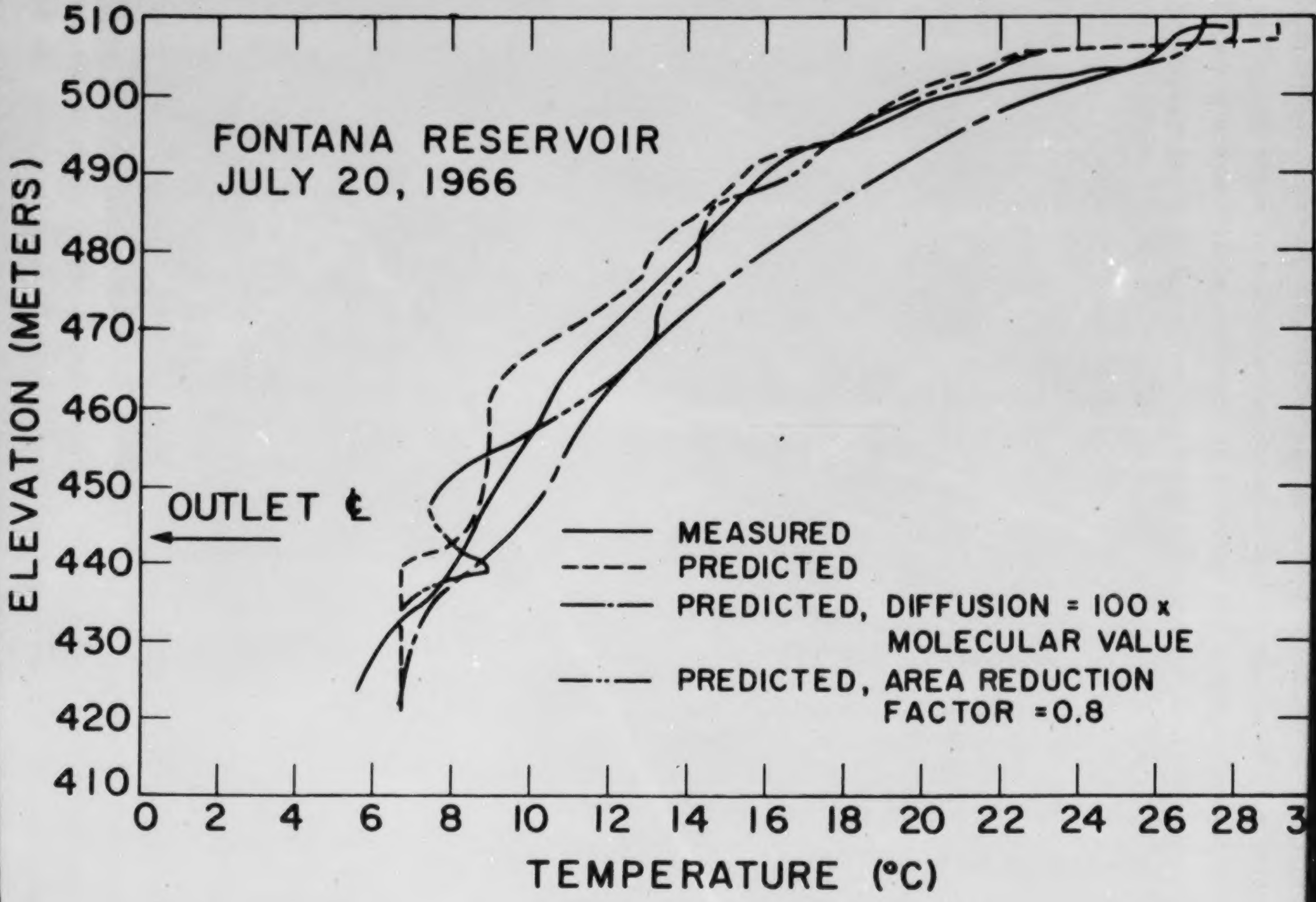


FIGURE 25. THERMAL SIMULATION IN DEEP RESERVOIR
(Huber and Harleman, 1968)

computations, but one day is the typical value. Since the WRE model is of a quasi two-dimensional type, it is applicable to weakly stratified situations in which the isotherms may be tilted. For such applications a preliminary knowledge of the temperature variation is necessary. The longitudinal segments are selected at locations where there are significant changes in the reservoir channel geometry. This model was tested against data available from Lake Roosevelt, behind Grand Coulee Dam. Figure 26 shows a comparison between the observed and computed values for the different segments of Lake Roosevelt. The comparisons are good, even with multiwithdrawals. Again, this model was developed for the purpose of predicting the natural thermal regime in the water body and temperatures of the downstream releases. However, the thermal discharges can be considered by specifying the corresponding temperatures to the inflows. The thermal discharges can be considered as a separate inflow, since the model is capable of handling many tributary flows. The segmentation may be such that the thermal discharge is directed into one segment. Care should be taken that the time step should be less than the smallest residence time in any of the segments.

The WRE model has also been used to simulate the thermal regimes of the Hungry Horse Reservoir and the Detroit Reservoir, for which the results compared well with the measured data. The U.S. Army Corps of Engineers has been using the WRE model extensively for planning purposes in predicting temperature regimes of reservoirs. For example, this model has been used to predict temperatures of The Koocanusa Lake formed by the Libby Dam on the Kootenai River, the Divorshak reservoir in Idaho, and the Lost Creek Reservoir in Oregon. The first two have been completed and the latter is under construction. The computer program of the WRE model can be obtained in the form of punched deck for a nominal cost from the U.S. Army Corps of Engineers, North Pacific Division.

Two other models to be considered are the Battelle Model (Battelle Laboratories, 1969) and the Hydrocomp Model (1974).

The Hydrocomp model, as it is available at the present time, comprises simulation of temperature and other water quality parameters in impoundments and rivers due to various changes taking place in the catchment area and the waterbodies. The composite program is called the Hydro-

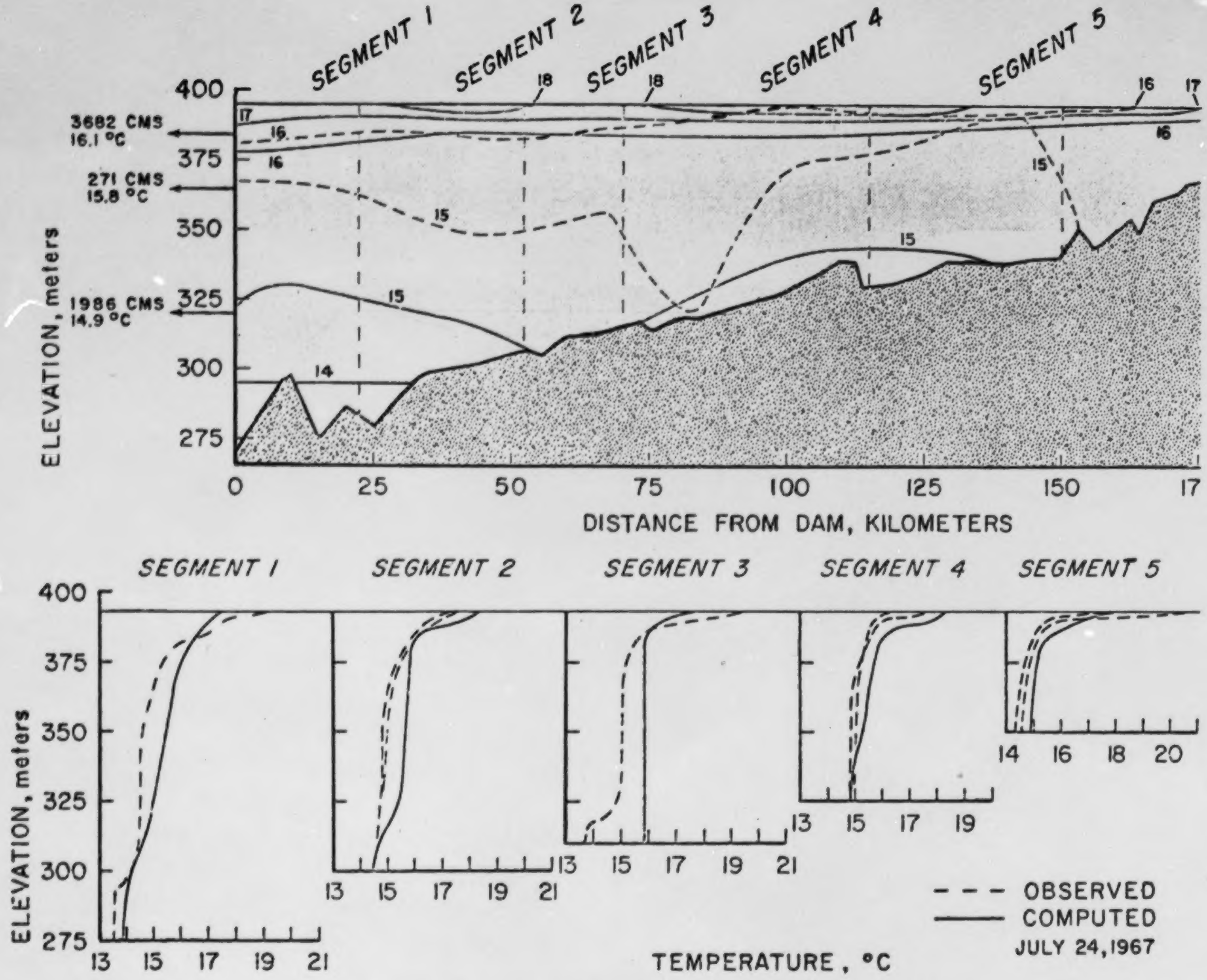


FIGURE 26. TYPICAL RESULTS FROM SIMULATION OF THE THERMAL REGIME OF LAKE ROOSEVELT (1967) (WRE Model)

comp Simulation Program (HSP) and has been used recently on the impoundments situated on the Columbia River (Hydrocomp, 1976). In this model, the user partitions the lake or reservoir into as many as nine horizontal layers and assumes each layer to be fully mixed. Heated discharges can be simulated based on the assumption that the discharge disperses uniformly within the layer into which it is injected. The water surface elevation is allowed to fluctuate, causing the surface layer to have a variable volume. A manual on the program is available to describe the quantity model and the interfacing with hydrologic elements.

The Battelle computer model is actually a modified and refined version of the Water Resources Engineers' multisegment program. The schematization of the water body is the same as that of the WRE model and is shown on Figure 27. Although the schematization is two-dimensional, flows are not modelled in true two-dimensional form since changes in water density resulting from temperature differences are assumed negligible. The hydrothermal program is in two parts, the first called CLIMA and the second TERMA. CLIMA is a generalized data input program which points and plots all hydrologic and meteorologic data. The second program, TERMA, simulates the reservoir thermal characteristics. For a three-segment representation of the lake or reservoir, the total execution time will be about three to four minutes for one year of daily simulations. The following figures give some of the results obtained by this model. Figure 28 gives a comparison with data obtained in the American Falls Reservoir on the Snake River in Idaho. The reservoir was divided into three segments and simulated results of vertical profiles compared well with measurements. Figure 29 shows the comparison of model results with data obtained in Lake Washington, with the temperature profiles shown for different days. From both comparisons, it can be seen that the model presents excellent simulation of temperatures. The Battelle model has also been used with similar results in the simulation of temperatures in Lake Wingra and Lake Mendota (Kimmel, 1974). The computer program and a user's manual are available at Battelle Pacific Northwest Laboratories and the EPA offices. A copy of the program deck can be obtained at the former office.

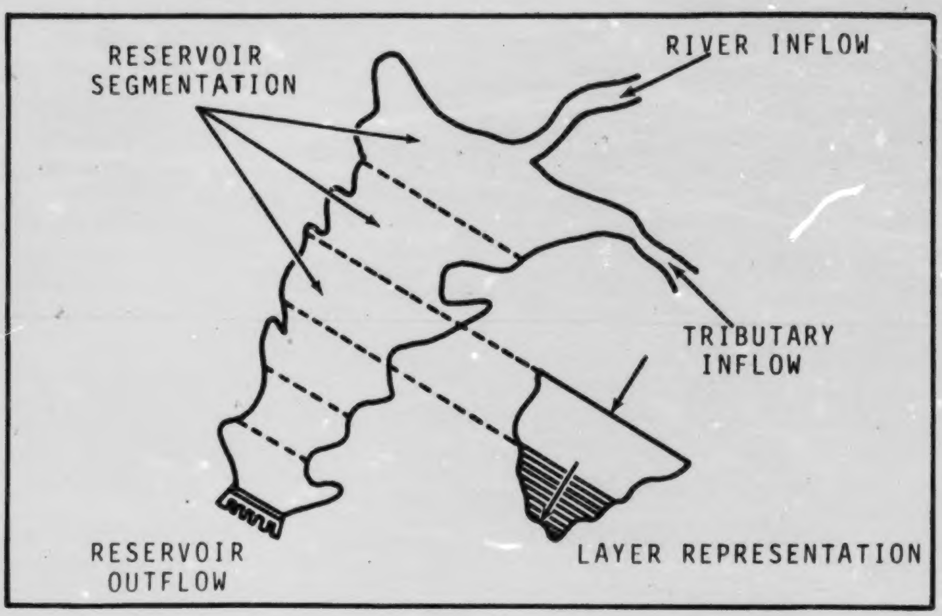


FIGURE 27. GEOMETRIC REPRESENTATION FOR THE BATTELLE DEEP RESERVOIR HYDROTHERMAL MODEL

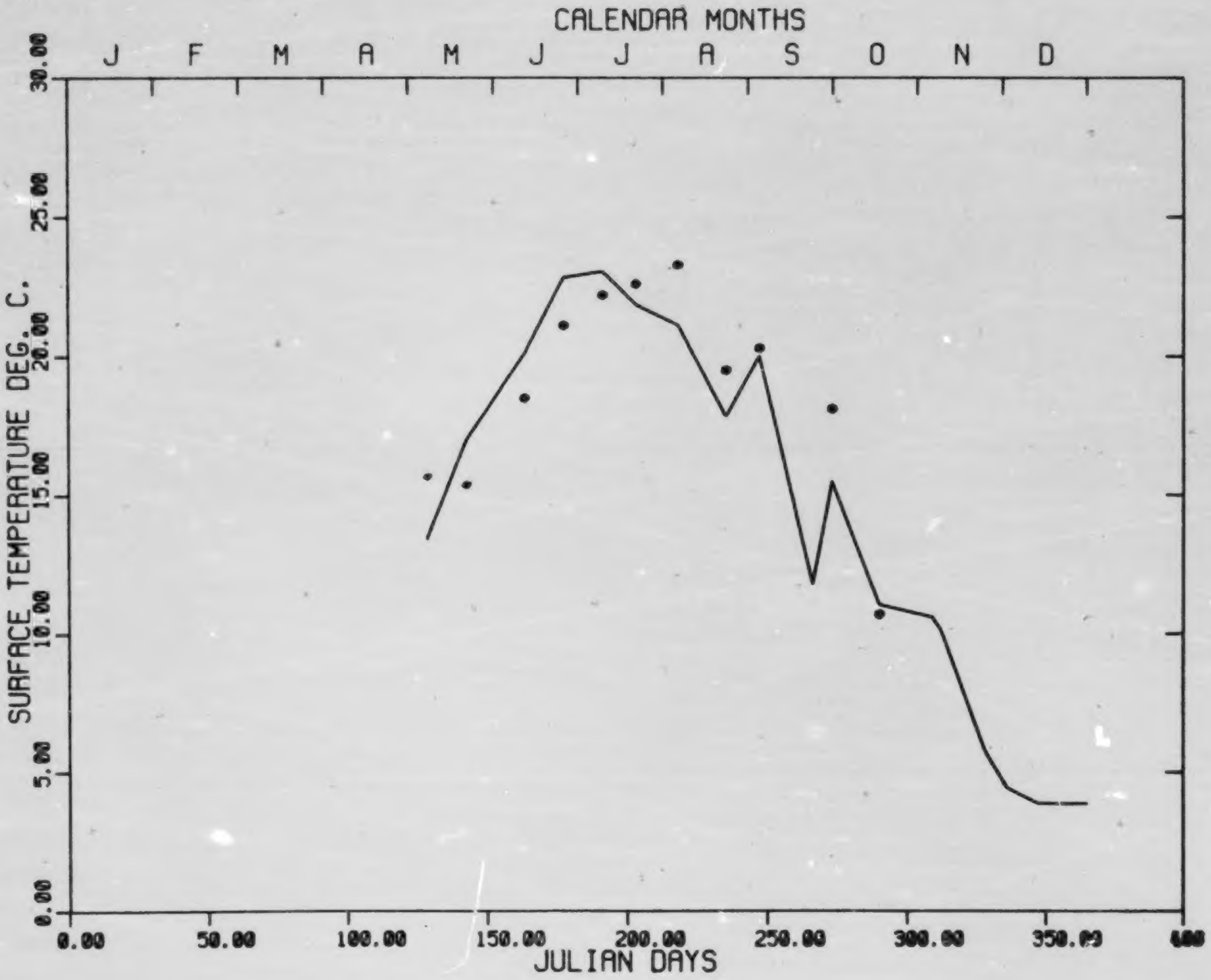


FIGURE 28. AMERICAN FALLS RESERVOIR - SURFACE TEMPERATURE vs. TIME (BATTELLE MODEL)

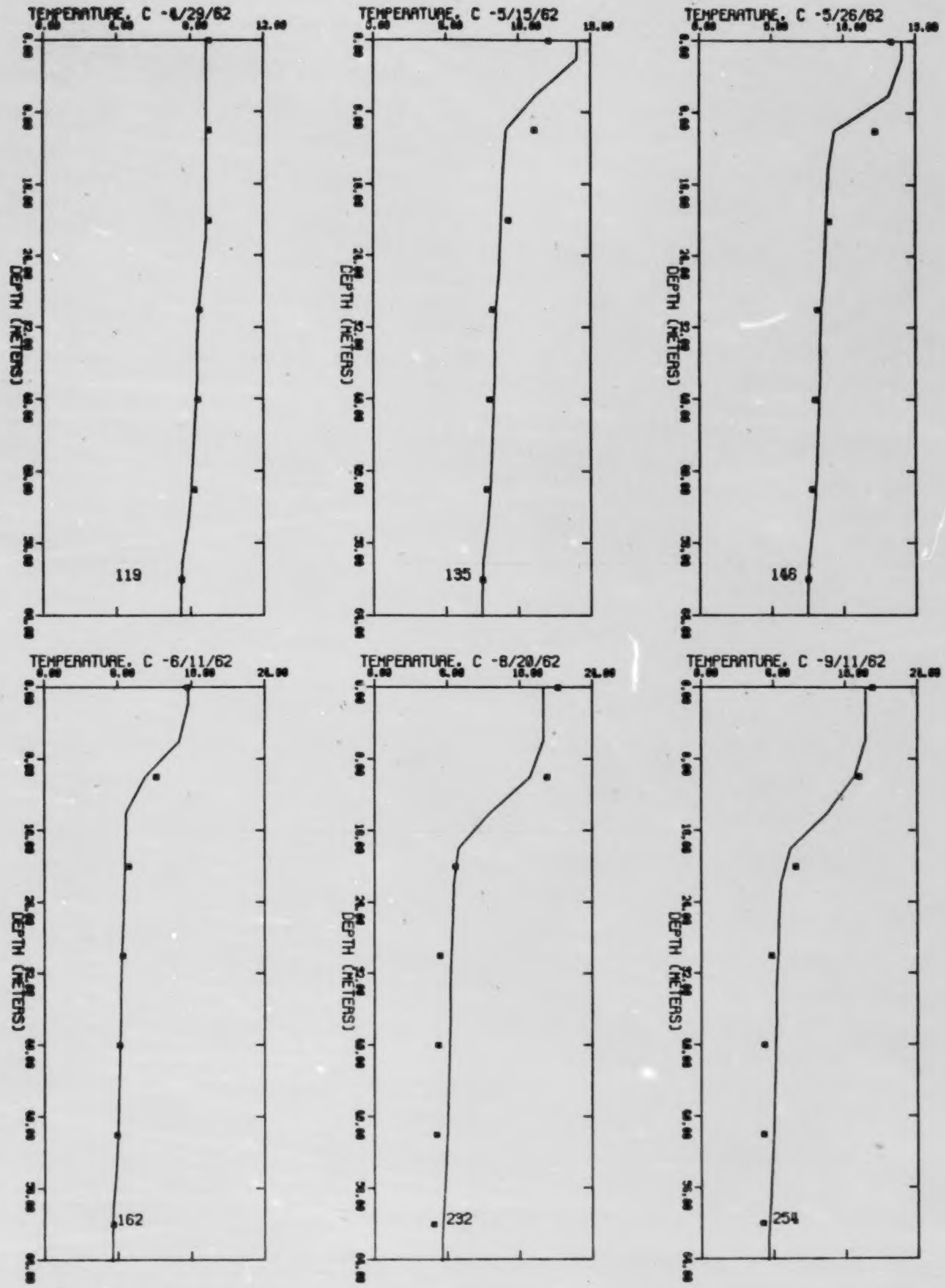


FIGURE 29. LAKE WASHINGTON INTERIM TEMPERATURE SIMULATION (BATTELLE MODEL)

Numerical models which account for density differences due to temperature change will automatically account for the phenomenon of density underflow discussed in section 4.5.2. The extent of the density underflow determines the type of analysis selected. Further, different types of water movement can be expected in the hypolimnion, each associated with significant mixing activity in these layers.

Based on simple channel flow hydraulics, the depth of the potential hypolimnetic flow, h_2, can be estimated. This involves an equation of uniform channel flow with discharge, bottom slope and bottom friction as variables.

The density difference ratio between the epilimnetic wedge and the hypolimnion, which is necessary for numerical modelling, can be estimated from the inflow temperature, T_o, and the equilibrium temperature, E (if the latter is representative of the stagnant epilimnetic wedge against the dam). The length of the wedge, L_1, can be determined by simple geometry relating h_2, the dam height, H, and bottom slope, s.

If h_2 is significant in relation to the depth of the reservoir and L_1 is a small fraction of the total length, then it is likely that a sectionally homogeneous analysis as used in the WRE model will be applicable at a particular flow rate. If, however, h_2 is small and L_1 is a large fraction of the total length of reservoir, then the planar homogeneous analysis as used in the M.I.T. model may be more appropriate for the same rate. Thus the parameter h_2 can be used to identify a flow-through water body and to determine which models mentioned are applicable for this situation. Later in this section it may be noted that a run-of-river impoundment will exhibit sectionally homogeneous characteristics during another part of the year.

4.5.3.2 Two-dimensional models. The two-dimensional flow equations are probably the ideal way to represent a long, narrow flow-through reservoir, since the assumption of lateral homogeneity is usually justifiable. In one-dimensional cases, the temperature is a function of depth only and the changes due to flow-through cannot be properly simulated. In two-dimensional representation, the temperature variation is a function of the depth and the longitudinal distance. Temperature variations along the longitudinal axis are represented, and consequently tilted isotherms can be simulated. Complicated circulation patterns, such as the pattern which might be caused by the inflow to the reservoir of cool, denser water or warm, buoyant water can be simulated using a two-dimensional scheme. A schematization for these types of models is given in Figure 30.

Roberts and Street (1975) developed a model for the two-dimensional simulation of thermally influenced flows. The Navier-Stokes equation is used to the longitudinal direction only, accelerations in the vertical direction being neglected. Vertical velocities are calculated from the hydrostatic pressure distribution and the equation of continuity. The heat transport equation is solved simultaneously to obtain the temperature distribution. Results of this model compared very well with the results of a laboratory-physical model of a reservoir, for which data were obtained covering different seasons of reservoir operations (ibid).

Ryan and Harleman (1973) presented a model for hydrothermal analysis in a stratified pond. This model is essentially a combination of a two-dimensional model in the surface layer with a one-dimensional model in the vertical direction for the subsurface layers. Entrance mixing of thermal discharges is accounted for and the surface layer thickness is computed using a simplified form of the Stolzenbach-Harleman (1971) model, in which the surface layer is assumed to be fully mixed. The equation of heat transport in the surface layer contains a time-dependent term and a convective term, and computes the net heat loss to the atmosphere. The longitudinal dispersion of heat is neglected due to the predominance of heat advection by means of the bulk velocity. In the subsurface layer, heat is transported in the vertical direction by advection and diffusion (as in natural reservoir models, such as that of Huber and Harleman, 1968). Selective withdrawals can be simulated in this model and a comparison of model predictions with measured data is given in Figure 31. Results were also compared with data obtained from Lake Norman. Some modifications to this model have been investigated by Watanabe et al (1975) and have been included in a finite element model.

4.5.3.3 Three-dimensional models. The prediction of temperatures in a laterally and vertically stratified reservoir is a three-dimensional problem. For this type of situation, a practical prediction of temperature

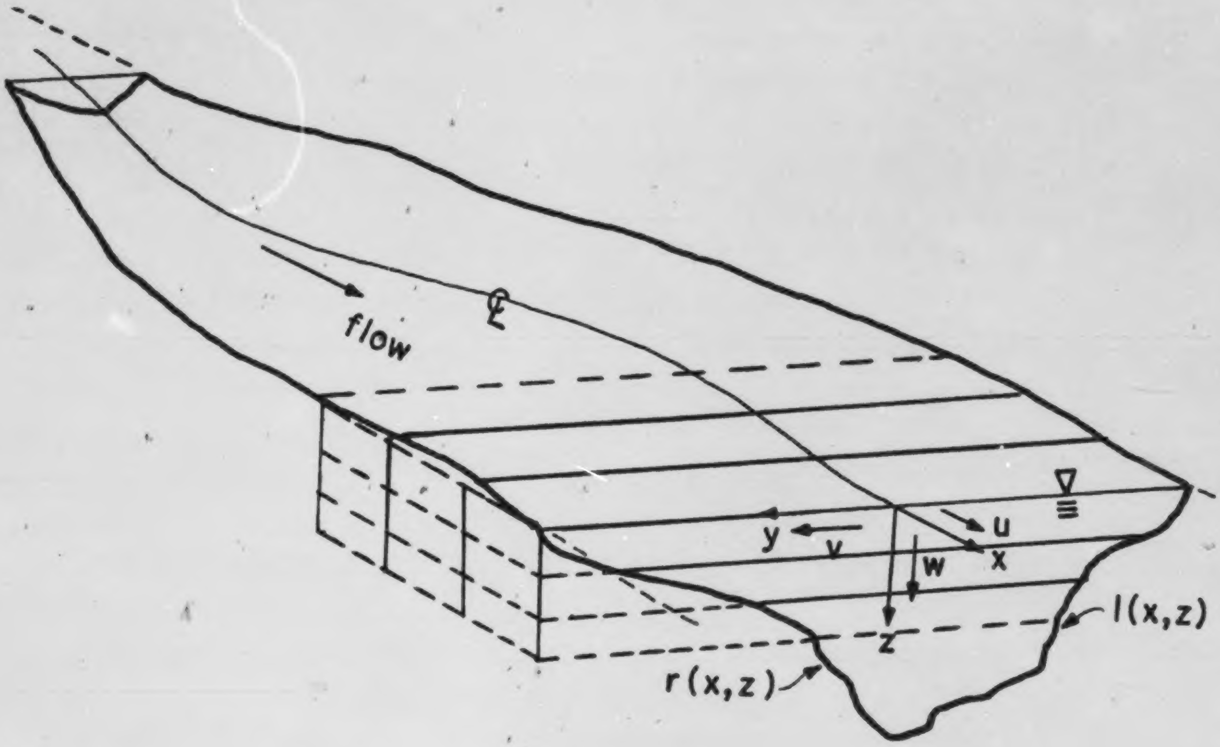


FIGURE 30. A TWO-DIMENSIONAL SCHEMATIZATION

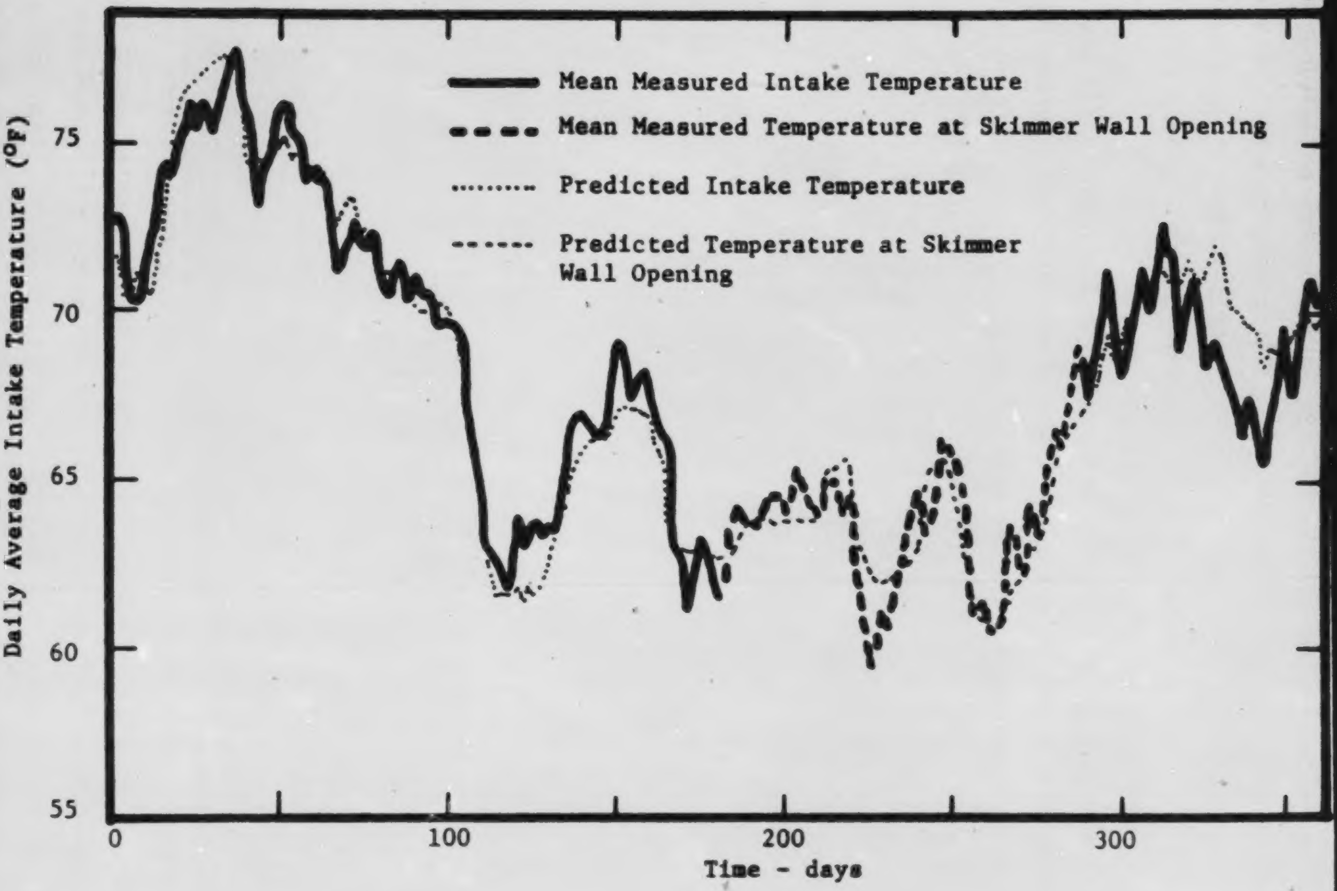


FIGURE 31. PREDICTED vs MEASURED INTAKE TEMPERATURES AT HAZELWOOD POND IN 1969. (Ryan and Harleman, 1973)

requires either a very complex simulation of the actual temperature and flow regime, or arbitrary assumptions to reduce the problem to a more manageable simplified thermal and flow regime.

Conceptually, any simulation can be approached by solving the Navier-Stokes equations of motion in three dimensions, together with the continuity equation and the heat transport equation. Boundary conditions must be specified for the heat flux at the water surface, and for the inflow and outflow quantities and temperatures.

Three-dimensional models are available (Leendertse and Liu, 1975; Spraggs and Street, 1975), for temperature prediction purposes. However, there are complicated questions involving finite differencing schemes, stability conditions, grid spacings, etc. which may be reservoir dependent.

Three-dimensional models require extensive computation on a large number of grid points if a relatively good solution is required. Implicit iterative solution techniques for such systems become costly and hence explicit schemes are preferred even though they require a smaller time step. Because three-dimensional models are expensive in computation, they should be used only in cases which require very accurate solutions, such as during the detailed assessment of a selected site.

Two and three-dimensional transient models, as mentioned above, are not in common use for the prediction of temperature in deep stratified lakes and reservoirs. This may be due to the fact that the modelling art for two and three-dimensional cases is constantly being improved and the computational costs are generally high compared to one-dimensional model costs.

In conclusion, it may be said that, at the present stage of model development and usage, only one-dimensional or quasi two-dimensional models are used with confidence in hydrothermal modelling of deep lakes and reservoirs. Only these types of model have computer programs which are readily available to users. The Battelle model, a quasi two-dimensional type, and an improved version of the WRE model are recommended for long and narrow lakes and reservoirs. To a certain extent, the density underflow situations can be simulated using the quasi-two-dimensional models by specifying the segments perpendicular to the direction of underflow. In cases of simple reservoirs and lakes with regular boundaries, the M.I.T. model is applicable.

5. HEATED DISCHARGE MANAGEMENT IN RIVERS

The approach to thermal discharge in rivers is in many ways different from the approach for lakes and reservoirs. Studies in rivers should consider turbulent flow, rapid mixing, the high rate of surface renewal, and the high surface area to volume ratio. These result in typically rapid re-aeration via the atmosphere, except during winter conditions of ice cover. Because of the short residence times in any particular reach of a river, the level of biological productivity is smaller than in natural lakes and ponds.

An additional feature of rivers that differentiates them from other water body types is that the bulk flow in rivers tends to be unidirectional (with the exception of tidal and backwater systems). Also, as the flow is confined to the channel, the effect of heated discharge from upstream plants on downstream discharges also becomes an important management feature.

Flows in rivers are largely determined in the natural condition by runoff from precipitation and infiltration into groundwater within the drainage basin. Runoff is also "stored" on the watershed as snow. The smaller the basin, the more rapid the response time of the downstream flow to rainfall events. Consequently, unless regulated, there is a wide annual fluctuation of average daily river flow rates. In addition, there is a great seasonal variability in the flow of most Canadian rivers used for steam electric cooling. In the mid-west, low flows commonly occur in the fall and while heated discharge will displace the river temperature regime in time, it may not significantly affect the peak temperatures. In the east, the warm summer months coincide with periods of low flow and heated discharge displaces both the time and peak of the existing thermal regime. Even within these periods, the hydrothermal consequences are variable as a result of unsteady rivers flows and fluctuations in plant heat rejection.

Heat dissipation in rivers is normally achieved by initial mixing and subsequently by dilution by means of tributary inflows. The natural diurnal temperature variations in the river are a significant factor as they follow closely the pattern of air temperatures (when these are above freezing). The high surface area to volume ratio of rivers causes the major input of solar radiation to be more than equivalent to the change in temperature caused by heated discharge from even large stations. The daily and seasonal temperature fluctuations and differences in channel characteristics and latitude all contribute to produce wide temperature variations in a single river channel at any one time. Even in the immediate discharge area, the thermal regime of the plume may lead or lag the natural temperature upstream or outside the plume. Thus, as the natural temperature of a river is controlled by climatic conditions, in many cases these impose a more significant effect on water temperatures than does waste heat (except on a local scale).

Natural stratification in fresh water reaches of rivers is not common. Rivers are generally well mixed both horizontally and vertically, and the thermal discharge will usually mix completely into the full river flow. The majority of surface cooling takes place over long downstream distances and tributary inflow volumes are usually the most significant cooling influence once fully mixed conditions have been established.

In shallow rivers, the heated discharge may impinge on the bottom, while in deep rivers, the discharge may form a backwater density wedge, moving upstream for some distance. Again, the extent and characteristics of these local effects are as much a function of the existing temperature of the river as of the particular characteristic of the heated discharge.

As a result of these many factors, the extent of modification of the existing thermal regime of a river by the discharge of condenser cooling water is influenced more by the hydrology, morphology and natural temperature regime of this water body category than of any other water body category discussed previously.

5.1 Management Alternatives

Excluding the Great Lakes Basin, by far the greatest number of Canadian steam-electric stations are located on rivers. The river stations are designed for once-through cooling. Table 6 summarizes the design aspects of some of these Canadian stations. Once-through cooling

TABLE 6. SOME THERMAL ELECTRIC GENERATING STATIONS ON RIVERS IN CANADA
(Installed Steam Generation of 20 MW or More*)

STATION	LOCATION	GENERATION	FUEL	UTILITY	TYPE OF COOLING	COOLING WATER DEMAND (cfs)	COOLING WATER - INTAKE SOURCE OUTFALL BODY	INTAKE DESCRIPTION	DISCHARGE TEMP. RISE °F (°C)	OUTFALL DESCRIPTION	REMARKS
Lambton G.S.	Courtright, Ontario	2000	coal	Ontario Hydro	once through	1552	St. Clair River	onshore at surface, canal ≈ 650' long, projecting into river	26.4 (14.7)	600 foot canal to surface, shoreline discharge downstream of intake	fish catch
Rossdale	Edmonton, Alberta	450	-	Edmonton Power	once through	-	North Saskatchewan	submerged and onshore, sub. to 6' below min. level & 3-4' off bottom	30 (16.7)	short canal to shoreline, discharge immediately downstream	-silt problem -benefit for treatment plant
Clover Bar	Edmonton, Alberta	330 (to 660 future)	-	Edmonton Power	once through	-	North Saskatchewan	surface intake projecting into river, graded apron and channel for silt bypass	30 (16.7)	short canal to downstream shoreline discharge by spillway	
J.C. Keith	Windsor, Ontario	264	coal	Ontario Hydro	once through	303	Detroit River	onshore intake canal ≈ 150' long, projecting into river	23.5 (13.1)	300 foot outfall canal to surface, projecting groins dorect discharge downstream	
Brandon	Brandon, Manitoba	237	coal	Manitoba Hydro	once through	200	Assiniboine River	weir on river, surface intake from forebay	35.8 (20)	pipe to downstream shoreline discharge	-cooling tower collapsed -low flow problem
Queen Elizabeth	Saskatoon, Saskatchewan	232	oil, coal, nat.gas	Saskatchewan Power Corp.	once through	322	South Saskatchewan River	three partially submerged structures	10-30 (5.7-17)	shoreline spillway type to downstream	-ice problem -benefit to water supply clarifiers
Selkirk	Selkirk, Manitoba	157	coal	Manitoba Hydro	once through	321	Red River intake, Cook's Creek outfall	surface intake projecting slightly into river	17-29 (9-16)	downstream outfall to creek ≈ 3-1/2 miles long running parallel to Red River	-
H.R. Milner	Grande Cache, Alberta	150	coal	Alberta Power Limited	closed cooling, mechanical draft, wet cooling tower	-	Smokey River	-	18 (10)	-	-
Gentilly 1 (experimental prototype)	S.E. shore of St. Lawrence River	250	nuclear	Atomic Energy of Canada Ltd. & Hydro Quebec	once through	446	St. Lawrence River	open channel canal ≈ 300' long	18 (10)	downstream open channel outfall ≈ 400' long. Surface discharge, low velocity	-
Gentilly 2 (under construction)	S.E. shore of St. Lawrence River	600	nuclear	Hydro Quebec	once through	±1050	St. Lawrence River	open channel combined with Gentilly 1	±24 (13-3)	combined open channel with Gentilly 1	
A.L. Cole	Saskatoon, Saskatchewan	108	oil, coal, nat.gas	Saskatchewan Power Corp.	once through	228	S. Saskatchewan River	partially submerged in small bay caused by recent bridge construction	19-25 (10.6-13.9) -tempering	submerged, open-ended pipe ≈ 40' downstream from intake	construction increased recirculation
Estevan	Estevan, Saskatchewan	65	coal	Saskatchewan Power Corp.	once through (recirculating type)		Souris River	shoreline intake	20 (11.1)	canal ≈ 3 mi. long to shoreline outfall upstream of plant	de-rate in summer due to low flow
Medicine Hat Generating Plant	Medicine Hat, Alberta	55 steam (75 total)	nat.gas	Medicine Hat Municipal Electric Light & Power	once through	130	S. Saskatchewan River	three submerged structures ≈ 7' below min. level	22 (12.2)	shoreline discharge & well, downstream of intake	frasil and algae intake problems
N.P.D. Nuclear	Rolphton, Ontario	22	uranium	Ontario Hydro	once through	66.5	Ottawa River	shoreline intake flush with banks	20 (11.1)	submerged outfall downstream of plant and angled at 45°	-

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*Numerical values are approximate only.

was also practiced frequently on rivers in the United States where the cooling water flow rate normally represents about 10% of the mean annual river flow and about 30% of the low flow. Typical condenser temperature increases are around 10°C. In recent years, however, offstream cooling modes have been required by legislation at many sites. These offstream systems have included cooling towers or cooling ponds, but the favoured alternative combines more than one cooling mode, such as helper cooling ponds combined with once-through cooling.

Both surface discharge and submerged outfall alternatives have been used at river stations, although of the 14 Canadian river stations larger than 20 MW, more than half have surface outfalls and all of the stations larger than 200 MW discharge at the surface. These outfalls are usually of the low velocity type, but may vary from spillway-type designs to open canals or pipes. In the United States, it is also common practice to discharge waste heat through an open canal. However, there are proportionately fewer river stations in Canada with submerged outfalls than in the United States. Again, these submerged alternatives can have a high or low velocity, can incorporate diffuser systems, and can be oriented in numerous ways, depending upon the river characteristics at the site.

The cooling water intakes for these river generating stations are as varied in design as are the outfalls. However, the three distinct categories that can be discerned are submerged intakes in the main river flow, shoreline intakes projecting into the flow, and shoreline intakes with a forebay or canal leading to the pumphouse (James F. MacLaren, 1975).

5.2 Examples of Canadian and American Practice

The discharge from most plants is carried by open canals to the river banks which may or may not be near the plant. For example, the 2000 MW Lambton Generating Station on the St. Clair River is not immediately on the river bank and the cooling water is released into a 600-foot long open canal to be discharged downstream of the intake. Similarly, the J.C. Keith Plant on the Detroit River, the Clover Bar and Rossdale Stations on the North Saskatchewan River, the Estevan Station on the Souris River, and the Selkirk Plant on the Red River have relatively short open canals leading to a low velocity surface discharge. The particular configuration of low velocity, surface discharge canals is typically very site specific, depending on river characteristics or the need for auxilliary cooling modes to satisfy regulations. As was mentioned in previous sections, however, low velocity discharge canals represent potential danger areas for fish due to the possibility of cold shock unless access to the canal is blocked.

The discharge channels can also be in the order of several miles in length. For example, the 65 MW Estevan Station is unique in that the discharge is carried in a canal about three miles upstream from the plant intake. This produces an on-stream recirculating system enabling a degree of flow regulation during low-flow periods and ice protection at the intake during winter. During the summer, however, heat build-up is significant and the plant is de-rated for biological and station safety purposes. The 157 MW Selkirk Station also discharges into a three-mile long channel. This channel is the main stream of Cooks Creek which runs parallel to the Red River and discharges downstream from the plant. Cold shock fish mortalities are occasionally experienced in this canal. However, similar cold shock and exposure problems are not observed at the 170 MW Indian River Plant in Delaware. This plant uses a two-mile long canal which results in a three-hour residence time for the cooling water discharge. The condenser cooling water temperature elevation is about 7°C above ambient. The temperature rise above ambient at the mouth of the canal is reduced to about 2.8°C and a further two miles downstream the elevation is just over 0.5°C. The river is regarded as being of very high quality and is not reported to be adversely affected by the discharge.

In another case, the four mile long ox-bow on the James River, Virginia serves as a discharge canal for the 1416 MWe Chesterfield Station. About 13% of the mean river flow is withdrawn for cooling. Problems with destruction of organisms are observed in the discharge canal and are associated with excess temperatures and chlorine.

In addition to the above-mentioned stations, several other variations in shoreline discharges are in use. For example, the 880 MW Wabash River Plant in Indiana discharges parallel to the shore via a discharge canal. However, the walls of the canal are designed such that the canal floods during high flows and mixing is promoted. During the low flow season, the canal causes the plume to "hug" one shore and this allows fish a "zone of passage" to avoid excessively high temperatures. Spawning is not affected by the discharge as the temperature rise is minimal in spring due to considerable dilution because of high river flows.

Another outfall variation has a shoreline discharge structure designed as a spillway. This alternative is used at both the 330 MW Clover Bar Station in Edmonton and the 232 MW Queen Elizabeth Station in Saskatoon and has eliminated fish access to the outfall conduit. Similarly, piped discharges may be advantageous for discharge as a plume.

The steam-electric stations at Brandon, on the Assiniboine River, and at Medicine Hat, on the S. Saskatchewan River pipe the heated discharge to low-velocity outfalls at the shoreline, and release the coolant through an open pipe and discharge well, respectively. There are apparently no significant biological effects.

Sumberged outfalls are not common for heated discharge into rivers in Canada. Only the Ontario Hydro NPD Rolphton Station and the Saskatchewan Power A.L. Cole Station have outfalls that are sumberged. The 22 MW Nuclear-Power Demonstration Plant at Rolphton on the Ottawa River discharges through a rectangular box structure. The outfall is near mid-stream, about 20 feet deep, and oriented to discharge downstream at about 45 degrees to the flow. The outfall of the 108 MW A.L. Cole Station in Saskatoon consists of an open-ended pipe discharging vertically in mid-stream located about 40 feet downstream of the intake. This short separation between the intake and outfall has, however, led to unintentional recirculation back to the intake and consequential heat buildup.

The effect of heat buildup is also shown on the North Saskatchewan River at Edmonton. The heated discharge from the upstream Rossdale Station, combined with several lesser sources within the city, are sufficient to prevent an ice cover in the area of the Clover Bar Station. There are obvious operational benefits at Clover Bar from the upstream discharge, as it is not necessary to recirculate a major portion of the discharge to the intake to prevent ice buildup. In this instance, it may also be that lack of direct recirculation of warm water between the intake and outfall of the Clover Bar Station means that there will not be attraction of fish to the intake area, and thus it constitutes a biological benefit. The disadvantage, and possible problem, of locating a new plant in the region of influence of existing thermal discharges relates to the potential for a cumulative temperature buildup which may exceed allowable tolerance limits of local species regardless of the outfall system used.

The Quad Cities Station in Illinois has been studied in detail and at one time used two 16-foot diameter diffuser manifolds with multiple ports. This provided better mixing but, nevertheless, the facility still discharged too great a thermal load to the river in summer months. Consequently, starting in May of 1974, the facility began discharging 47% of the heated water into the river through the diffuser system, while the remaining 53% of the cooling water was discharged into a spray canal and, by means of a spillway and return canal system, it was recirculated to the intake canal (Industrial Biotest Laboratories, 1974). This latest system has apparently satisfied the Illinois-Iowa state laws for thermal effluent discharge.

Submerged or partially submerged intakes in the main river channel are used at four large Canadian stations, all of which are on the North or South Saskatchewan Rivers. For example, the intake for the newest units of the 450 MW Rossdale Station in Edmonton is an open submerged aquaduct six feet below the minimum water level and is raised about three feet off the bottom to avoid major silting problems. This offshore intake is combined with an older intake on the river bank which supplies the cooling flow for the original units. The 108 MW A.L. Cole Station in Saskatoon also has an offshore intake. The concrete structure is partially submerged and draws from the downstream face. At this station, occasional sand entrainment is experienced under the ice.

Partially submerged offshore intakes are also used at the 232 MW Queen Elizabeth Station in Saskatoon. Three triangular concrete risers draw the cooling flow from just below the river surface. They are arranged perpendicular to the river flow and intake at two of the three faces. The Medicine Hat Generating Plant also uses three offshore intakes. These structures, however, are completely submerged to about seven feet below minimum level and are parallel to the banks. This arrangement is used to advantage during periods of frazil ice formation, which affects both of these stations. Heated discharge is intentionally recirculated through the upstream structure to keep the two downstream intakes clear of ice accumulations at the Medicine Hat Station.

The most common shoreline intake design incorporates a forebay or an intake canal leading to the pumphouse. On the larger Canadian rivers, stations such as the Lambton, Gentilly and J.C. Keith plants have intake canals that are usually several hundred feet long and also include projecting offshore jetties. Stations such as Brandon and Estevan on smaller rivers do not have these projecting jetties but instead use shorter recessed forebay channels. Although fish entrapment and impingement is noted at many of these stations, there are, generally, no major ice problems.

The 330 MW Clover Bar Station in Edmonton and the 157 MW Selkirk Plant on the Red River also have pumphouses on the river banks. However, these structures project slightly into the river. The cooling flow is drawn from below skimmer walls and the coarse screening takes place in the river itself at the face of the intake structure. Clogging by silt, leaves, and frazil ice does not appear to be minimized by this type of design.

5.3 Hydrothermal Design Considerations

In general, river hydrology, morphology, biology and climatic conditions are significantly different from site to site and preclude a definition of the best available detailed design for all locations. Concerning the hydrothermal aspects, however, an important consideration is to provide time-temperature conditions that permit survival of aquatic species in question. As explained in following sections, hydrothermal design is governed by permissible temperatures. Entrainment is also a factor to be considered and one in which the key aspect is the percentage of entrained species in the cooling flow (Section 2).

Controlling the time of travel at elevated temperature is important for both passage through the power plant and along the plume, and for entrainment of species into a plume. One method of providing rapid mixing is to provide a high velocity jet discharge at the river bank or to provide a diffuser outfall in the main channel of a deep river. The turbulence induced by the discharge enhances the natural mixing and provides a rapid drop in the excess temperature in the immediate vicinity of the outfall. The jet discharge may, however, also induce scouring at the outfall, present localized navigational problems, and cause entrainment of floating or migrating species into the plume. Certain fish species may even be attracted to this type of discharge. In order to minimise the disruption of benthic organisms or the possibility of complete blockage of fish migration routes, the alternative of a single high velocity discharge to the surface or to an intermediate depth may be preferred. If angled downstream and submerged at low water, a zone of passage will be provided at the opposite shore. This alternative, however, contradicts most existing practice and regulations and is usually omitted in preference to the following alternative.

It is usually possible, by appropriate outfall design, to rapidly mix the discharge into the river flow or stratify (float) the discharge on the river surface, and it may be argued that it is preferable to provide initial stratification of the heated discharge. Hence, a low velocity, surface discharge from a canal or pipe may be considered. As mentioned previously, the open canal discharge alternative has frequently been used at Canadian steam stations. The typical design is a simple low-velocity, box-duct collector set on the shore. The low velocity discharge stratifies as it mixes slowly with the river. If the river flow is not rapid, a zone of cooler water will be maintained both beneath the plume at the outfall and at downstream reaches where mixing and cooling have reduced the mixed flow temperatures. Again, however, the floating plume is not without potential biological problems. Shoreline impingement of the heated discharge is promoted by this design and blockage of the mouths of tributary streams may be difficult to avoid. Riverine systems are noted for high benthic biological productivity in areas of high water flows. If the temperature rise from low velocity discharges is too high, certain benthic invertebrates may be excluded from the river and nuisance accumulations of vegetation may be accelerated.

The river geometry, as it relates to the hydrodynamics of river flow, is also important in the outfall design. In regions characterized by meandering streams, a discharge site on a curve can result in two distinct patterns of plume movement. A discharge to the inside of a curving section will be directed across the river and mix with the full stream width, whereas a discharge on the outside of the curve will "hug" the river bank for some distance downstream. The angle of the discharge to the bank can similarly affect the orientation of the plume. If the outfall design discharges in a downstream orientation, the plume will again tend to adhere to the river bank on the discharge side. If discharged across the path of flow, the plume will mix rapidly through the width and depth of the flow. The optimum discharge angle will be between these two alternatives and must, therefore, be considered at each site.

In other instances, seasonal variations in rainfall combine with the river geometry to cause flooding. Long canals are needed through floodplains to reach a station required to be located at some distance from the river banks. Excessive length of these canals is undesirable because of the increased time of exposure for organisms pumped through the plant. The channels themselves often become residence areas for those species attracted to the discharge or intake and, thus, become potential sites for serious cold shock mortality or entrapment.

With either the high velocity or low velocity designs, a backwater wedge of the heated discharge may form and result in recirculation back to the intake. To alleviate this problem, the combined study of intake and outfall alternatives becomes important. The recirculation problem is usually most noticeable with surface intakes and can be alleviated by a submerged intake, upstream of the outfall and beneath the density wedge.

During Canadian winters, however, it is often desirable to encourage a degree of recirculation to inhibit formation of frazil ice in the immediate area of the intake screens. The design option now most commonly selected includes a recirculating duct to return a portion of the heated discharge directly back into the intake pumphouse. The historical trend in ice control has, however, varied considerably from this preferred method.

Older stations have often released the full heated discharge flow at an upstream point to keep the entire intake area free of all ice. At other stations, two canals have been constructed to enable upstream discharge during the winter and downstream discharge during the summer. Several of the problems mentioned previously occur in either of these older alternatives and, if heated discharge is required for ice control, the recirculating duct to the pumphouse is now recommended.

The importance of intake design is not limited only to the prevention of ice buildup and recirculation during summer. Most riverine organisms are flow-oriented and induced flows into the intake may attract fish to potential areas of entrapment and eventual entrainment into the cooling system. This effect is now considered more serious than the "plume effect". Fortunately, the potential for successful exclusion of these species from possible intake entrainment is greatest in river systems. A number of guidance-screening devices have been developed for particular application on rivers and protect both mobile and sessile species from possible damage (Downs and Meddock, 1974). Intake design and construction may also be important to the river morphology. Dredging channels inducing silting or scouring may greatly influence the habitat and community structure of benthic organisms. Removal of cooling water from tributary mouths can affect the important dynamic character of silting and sand bar formation.

5.4 Biological Considerations

The biological effect of waste heat on rivers that is most widely publicized, and is doubtless extremely important because it represents a biological indicator of thermal pollution, is the effect on fish. A thermal effluent will affect not only the indigenous fish population but more importantly, it may affect the (spawning) migration of anadromous fish. The integrity of a fish population is modulated by a balance between recruitment and mortality. The major form of recruitment involves reproduction-recruitment of fry. Factors inhibiting reproductive success of fish, acting chronically, are likely to exert a profound deleterious effect on the population. If the effluent from a thermal power plant were to block or otherwise significantly inhibit a spawning run, the local population of that fish would naturally be affected since access to spawning grounds would be blocked.

Apart from fish themselves, the bottom or benthic community downstream from a thermal outfall is extremely important, not only because it provides food for resident fish, but because indicator species reside in the benthos, which can be used to gauge the impact of the power facility.

Other biological parameters which are monitored and which may play an increasingly important role as indicators of pollution as water velocity decreases (i.e. from lotic to lentic habitats) are submerged macrophytes and their epiphytes, and the plankton.

When choosing a site and a mode for discharge of heated water (e.g. discharge canal vs. submerged diffuser pipe), the temperature regime and flow of the particular river, as well as the complex and diverse responses of aquatic organisms to temperature changes in the particular river, must be taken into account. If, for example, the plant were to be situated on a large northern river, such as the Columbia or North Saskatchewan River, having a large flow, the particular site and mode of discharge chosen would be less important than for a southern river (e.g. Savannah) or a river with seasonal low flows (e.g. Assiniboine River). Complete mixing of thermal effluents can be applied to large rivers with relatively few detrimental effects on the biota.

In the Columbia River, for example, the heated discharge from the Hanford Plant has no effect on the spawning migrations of Pacific salmon. Thermal input from this plant adds only a small increment to the river temperatures during the annual cycle. Although the majority of the discharge is released near the river banks, the plume affects the entire river volume because of rapid initial mixing.

On the other hand, the effects of man-made impoundments along the Columbia have exerted a considerable effect on the thermal regime of the river, as well as inundating large reaches of spawning territory. By comparison, the Hanford has little effect on the Columbia (Nakatani, 1969).

In the North Saskatchewan River, the effect of the Clover Bar Station is noticeable only in the immediate vicinity of the outfall. Here, fish populations are most numerous, the fish attracted being goldeye, walleye, shiners and northern pike. There have been no reports of fish kills due to thermal shock (Western Research and Development, 1975). No definite conclusions were arrived at with respect to benthic organisms at Clover Bar. In contrast, at the Gentilly Plant on the St. Lawrence, the benthic organisms (gastropods were monitored) were reduced in number only immediately below the outfall.

This mortality of gastropods was thought to be due to cold shock because of shutdowns rather than the result of elevated temperatures (Vaillancourt and Couture, 1975). Typically, there appears to be an increase in number of organisms and diversity of species in the vicinity of a thermal outfall even in warm water rivers (i.e. more southern rivers). This phenomenon of thermal "enrichment" is most noticeable in warm water rivers during winter months when organisms exist towards the lower end of their tolerance ranges. Hence, at the Chesterfield Plant in the James River, the thermal plume does not seem to affect 36 species of warm water fish found in the river, including catfish, carp, centrarchids, gizzard and American shad (Jensen et al, 1974). Primary productivity (of phytoplankton) is increased in the area of heated effluent in all but the warmest summer months, at which time a depression takes place (Smith and Jensen, 1974). Chlorination rather than heat may be the cause of deleterious effects that do occur.

At the Quad Cities Station on the Mississippi River, the thermal effluent caused an elevation in plankton and periphyton production in winter, while a depression in the summer was thought to be due at least in part to chlorination (Industrial Biotest Laboratories, 1974). It is typical for the benthic communities within the influence of the thermal plume to undergo shifts in species composition, often towards a greater diversity and to greater total numbers of organisms. Hence, at the Quad Cities Plant, the total number of benthic organisms is higher at all times in the discharge area compared to the intake area, but diversity is increased in winter and decreased in summer (Industrial Biotest Labs, 1974).

In the discharge canal at the Haddam Neck Plant on the Connecticutt River, there has been a species shift from diatoms to blue-green algae. There has been, in addition, an increase in the variety of benthic organisms, which naturally consisted of midges, worms and freshwater clams, and now also includes the larvae of beetles, dragonflies and damselflies. This increase in diversity and number might have been caused by habitat changes from the flushing effect of the effluent (Merriman, 1970). It should be noted that, at most facilities, the discharge causes a change in benthic habitat through the removal of silt by scouring action produced by water velocity. The effects of heat, therefore, are compounded not only by the effects of chemical discharges but also by the effects produced by water velocity.

At the Haddam Neck Plant on the Connecticutt River, the indigenous warm water species in the river appear not to be affected by the thermal discharge, nor are the migrations of striped bass, alewife or shad. The condition of the catfish in the mile-long discharge canal, however, is poor, even though there seems to be an abundance of food present. It is thought that the increased metabolic demands placed upon the fish by the elevated temperatures in the canal are responsible for their poor condition (Merriman, 1970).

In most cases, from the influence of the thermal discharge from river-situated plants is confined to the benthos in the immediate vicinity of the point of entry of the warm water into the river. Fish which are able to avoid this area do so, and are generally not affected. Only when fish become entrapped in a discharge canal will there be very significant effects, unless a long down-stream reach is heated. Summer fish kills which have been reported, such as the one at the Brandon Plant on the Assiniboine River in 1973, may also be the result of "natural" fish kills as well as mortalities due to condenser temperature rises. The natural mortalities are a periodic phenomenon in warm water rivers, occurring when ambient temperatures at very low flow significantly exceed 30°C.

In the Assiniboine River, there are periods in the summer months, particularly in July and August, when minimum flow conditions may coincide with maximum ambient water temperatures. During such times, a major proportion of the river flow may be diverted through the Brandon Plant to fulfill its once-through cooling requirements. When this happens, downstream water temperatures will be well above 30°C, a temperature generally considered to be the danger limit for many aquatic organisms, particularly fish. Coupled with subsequent decreases in dissolved oxygen due to lowered solubility at high temperatures, these conditions provide a habitat very inhospitable even to warm water fish.

As mentioned in previous sections, the special case involving discharge canals represents potential danger areas for fish due to the chance of cold shock. For example, the Martin's Creek Plant, Pennsylvania, rated at 265 MWe, uses cooling water at a rate of about 270 cfs with an average condenser temperature rise of 14°C. Studies carried out by Trembley (1960-1961) and Coutant (1962) reported a predominance of blue-green algae, a common indicator of thermal pollution, within one-half mile of the discharge in summer. Upper tolerance limits for the biota varied between 32 and 35°C and fish were observed to congregate in the discharge canal in cooler months, but, again, cold shock was not observed.

It may be concluded that, as mentioned earlier, the major impact on riverine biota is exerted by climate and, unless a relatively large power plant is located on a relatively small river, the biological effects resulting from the operation of the plant tend to be localized in the reach of river (comprising several hundred yards to a mile) in the vicinity and primarily downstream of the plant. Serious consideration must be given to large power facilities proposed for location on warm water rivers or rivers which support anadromous fish.

5.5 Hydrothermal Modelling for Rivers

Studies related to the prediction of temperature in rivers subject to thermal discharges have concentrated mainly on the fully-mixed condition, i.e. uniform cross-sectional temperatures. In some fully-mixed cases, the temperature decay can be analyzed in a simplified manner by using an analytical approach, by involving statistical analyses of observed data or by curve fitting techniques. In cases requiring detailed results or where data are limited, a numerical analysis can be used to solve the momentum and heat transport equations.

5.5.1 Analytical approach

An overview of some studies reporting independent comparisons of computed and observed temperatures can provide much information on the present state-of-the-art of temperature prediction in rivers. For example, Raphael (1962) presented computations of mean monthly temperatures on the Columbia River using meteorological data from a distant weather bureau station. He computed mean monthly equilibrium temperatures using the Lake Hefner windspeed function (Marciano and Harbeck, 1952) and found that his results agreed with observed mean monthly temperatures within a few degrees for a reach of the river unaffected by impoundments or heated discharges. Velz and Gannon (1960) computed equilibrium temperatures as five-day averaged values assuming fully-mixed conditions at the discharge point. The computed temperatures were within 1.5°C of the data measured at the downstream points.

Gameson et al (1959) used a curve fitting technique to relate a temperature equation based on an exchange coefficient and a temperature difference, to a series of observations over a one-week period on a small stream in England. The observed temperature at a particular point fluctuated with variations in the generating plant loading and varying meteorological conditions, and also decreased from point to point downstream. It was observed that there were significant differences in the heat exchange coefficients calculated for the different reaches of the stream. If the general equation is based on a single exchange coefficient, the prediction of downstream temperatures is not normally accurate.

A problem similar to that of heated discharge to a river is the release of cold water from a reservoir to a river. Zeller (1963) reported work involving the prediction of diurnal variations of downstream temperatures following simulated release of water from the proposed Tiller Damsite on the South Umbqua River in Oregon. The periodicity of temperature variation at a particular point was assumed to be the same as that of the observed values. Assuming a steady flow at constant outlet temperature, expected downstream temperatures were calculated for various heat exchange coefficients based on time of travel between fixed points.

Short-term predictions of temperature can lead to erroneous results if the meteorological parameters are not accurately evaluated. For example, Messinger (1963) presented the results of a study made by the U.S.G.S. in October 1962 at Shawville, Pennsylvania on the west branch of the Susquehanna River. In this study, which covered a period of about 24 hours, a term-by-term evaluation of the heat balance components was carried out. The decay of predicted temperatures was much slower than observed. The discrepancy was attributed to the inaccurate evaluation of incident solar radiation in shaded reaches of the river.

The prediction of river temperature is also difficult in the immediate vicinity of the power plant's outfalls. This is because the extent of mixing in rivers is not easily estimated. As the heated discharge travels downstream along a river, it disperses laterally. The discharge temperature is reduced by this lateral dispersion and also by surface cooling. In addition, the discharge will usually form a wedge of heated water in the upstream direction. This has been a classical problem in the design-related study of recirculation and intake-outfall siting. The study of hydrothermal mechanisms in an existing situation is often facilitated by previous measuring programs. These can provide qualitative descriptions of the factors affecting the distribution of heat under different flow and plant operating conditions. An example of a review of mathematical studies to predict temperature distribution patterns near outfalls in rivers is given in a M.I.T. (1975) report.

5.5.2 Fully-mixed excess temperature

The parameter common to the following hydrothermal analyses of stream flows is the fully-mixed excess temperature. The point at which complete mixing occurs in relation to the discharge point will vary in different situations. An analysis to determine this distance will involve two or three-dimensional considerations in the immediate vicinity of the outfall. The analysis will include consideration of dispersion and convective effects. In some situations, the conventional "near field" hydrothermal modelling will be applicable.

In the near field, it is necessary to account for the entrainment of ambient fluid into the jet, due to the momentum of the jet itself. Stolzenbach and Harleman (1971) developed a comprehensive three-dimensional near field model. A less sophisticated two-dimensional near field model is that of Motz and Benedict (1970). In the intermediate field, both entrainment (mixing) and surface cooling are important in determining the temperature regime in the river. Edinger and Polk (1969) described the intermediate field in both two and three-dimensionl models and Lau (1971) introduced the virtual source concept for simulations in this zone. The Motz and Benedict model assumes that the predominant factors affecting the momentum flux across any lateral slice of the jet are the entrainment of the lateral crossflow momentum and the eddying at the jet boundary. Ambient turbulence and buoyancy are assumed to have a negligible effect on plume dynamics and heat transfer within the jet. The model can be useful in determining the jet trajectory, centreline temperature, velocity and plume width. The Stolzenbach-Harleman model predicts the distribution of temperature and velocity in three directions within a jet defined by the predominance of jet momentum over the effects of ambient turbulence. Horizontal and vertical entrainment of ambient water is related to the jet centreline velocity by entrainment coefficients.

Edinger et al (1974) presented graphs indicating the distribution of excess temperatures near the outfall as a function of the dimensionless longitudinal distance and width. Surface cooling is neglected, the parameters involved in the calculations being flow, width, depth and dispersion.

These two models were applied for the proposed Gentilly Nuclear Station in Quebec by Lariviere et al (1975). The existing thermal station at Gentilly uses St. Lawrence River water in its once-through cooling system, returning the cooling waters to the river via a discharge canal. A comparison of measured temperature with the temperature predictions of the two models indicated that much better agreement was obtained using the two-dimensional Motz-Benedict model. The authors conclude that the assumptions of the two-dimensional model were valid for that particular location and it appears that the model is more flexible and easier to calibrate than the three-dimensional model.

In the downstream reach, however, the fully mixed excess temperature Θ_m can be computed from the formula:

$$\Theta_m = \frac{H}{\rho C Q} \qquad (1)$$

where: H = heat rejection rate of the power plant,

ρ = density of water (lb/ft^3),

C = specific heat of water (Btu/lb/^{o}F),
Q = flow in the river (cfs).

Since the heat rejection rate of different types of power plants vary for each unit of electrical power produced, Equation (1) may be conveniently expressed in the form:

$$\theta_m = \frac{RG}{\rho CQ} \qquad (2)$$

where: G = power generated by the plant (MW),
R = a factor which determines the heat rejection rate per unit of electrical power generated (Btu/hr/MW).

Figure 32 shows data interpreted for the Brandon Generating Station in Manitoba. The fully-mixed excess temperature is plotted against power generated per unit flow in the Assiniboine River. Though a straight line variation was expected, most observed temperatures were less than those given by the theoretical line. Under normal circumstances, several factors may lead to this type of differences (James F. MacLaren, 1976):

a) short-term variations in river flow and plant loading that are unaccounted for in Equation (2);
b) heat storage or dissipation of heat to the atmosphere in the reach between the plant intake and the point downstream where complete mixing is achieved;
c) difficulties in measuring small temperature increases at low plant loadings or high river flow;
d) unaccounted-for dilution water entering the flow from below ground or from surface sources downstream from the point of discharge; and,
e) effects of longitudinal dispersion.

It is indicated clearly in Figure 32 that the fully-mixed excess temperature, as computed from plant loading and river flow, is an upper limit that may be approached but seldom achieved in practice.

The above factors show that, because of the uncertainties involved in the prediction of fully-mixed excess temperatures using Equation

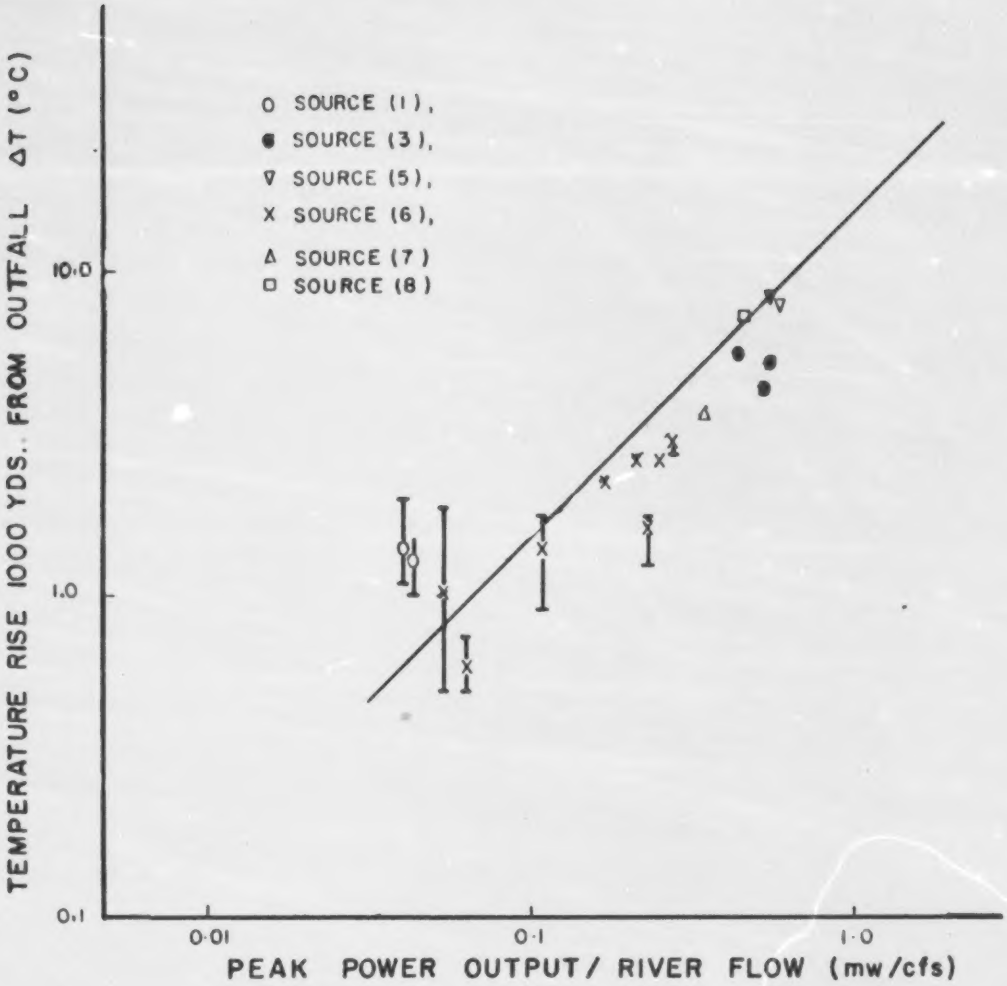

FIGURE 32. FULLY-MIXED EXCESS TEMPERATURE ON THE ASSINIBOINE RIVER FOR DIFFERENT POWER OUTPUT PER UNIT RIVER FLOW

(2), the results should be interpreted statistically. This type of analysis is more realistic in a situation where the plant loading and river flow varies over a wide range. Table 7 presents data obtained from the Assiniboine River and the computed joint flow/load probability distribution. The joint probability figures give the percentage of time in which the plant loading and river flow fall within specified ranges. Each joint probability figure is associated with a fully-mixed excess temperature and the results should be interpreted as the percentage of time in which a particular fully-mixed excess temperature is exceeded. For example, from Table 7, maximum temperature excesses (^{o}C) of 8.0, 5.0, 3.0, 2.8 and 2.0 are, respectively, exceeded on 0.1, 10.1, 27.0, 30.0 and 46.0 percent of the days.

5.5.3 Zone of partial mixing

As stated above, the distance below a thermal discharge at which complete mixing over a cross-section is achieved is site-dependent. For example, when the cooling water flow is large compared to the river flow and width, complete mixing will occur rapidly. However, when the river is wide (or deep) and the plant flow small, the partially-mixed state may persist for a considerable distance downstream. Under these circumstances, this zone may become important. Commonly, the rate at which the heat input spreads laterally across the river with increasing downstream distance is of most interest.

Edinger and Polk (1969) presented two and three-dimensional solutions for a discharge along a river bank whereby the dispersion laterally, or laterally and vertically, can be traced as the discharge is carried downstream. They emphasized the use of the models for predicting the surface area enclosed by a given isotherm rather than the actual spatial distribution of temperature.

Estimates of the lateral and longitudinal dimensions of the plume can also be made. Lau (1971) has taken a somewhat different approach in formulating a two-dimensional model by explicitly introducing the concept of a virtual source to account for initial mixing. It can be used to determine the temperature distribution at any section downstream of the heat source. The location of the virtual source is dependent upon

TABLE 7. JOINT PROBABILITY FOR RIVER FLOW AND PLANT LOADING - ASSINIBOINE RIVER AT BRANDON GENERATING STATION (November Data 1971-75)

RIVERFLOW cfs	PLANT LOADING (MWe)						Marginal Percentages
	40	40-80	80-120	120-160	160-200	200	
200	0	0	0	0	0	0	0
200-400	0	1.32	1.32	0	1.33	6.66	10.66
400-600	1.99	1.99	4.65	2.66	3.98	6.65	21.99
600-800	0.66	0	1.99	0.66	0	3.32	6.65
800-1000	5.32	1.99	5.98	3.32	4.66	2.0	23.33
1000-1200	11.99	1.32	1.32	0.66	1.32	0	16.66
1200-1400	0	0.66	1.32	0	0	0.66	2.66
1400-1600	0	0	0.66	0	0.66	0.66	1.99
1600-1800	7.98	0.66	1.33	0.66	1.32	0	11.99
1800-2000	0.66	0	0.66	1.33	1.32	0	3.99
2000	0	0	0	0	0	0	0
Marginal Percentages	28.65	7.99	19.32	9.33	14.65	19.99	99.99

the characteristics of the actual outfall. Methods of determining this point relative to the discharge are generally not well developed. However, the distance between these two points is typically a few hundred feet. The assumption of negligible surface heat losses made in both formulations is reasonable. Both are recommended for use in determining preliminary estimates of behaviour in the partially-mixed zone.

5.5.4 Analytical considerations

Analytical models for the prediction of temperatures in rivers are easy to "build" as compared to those for lakes and reservoirs. A good analytical model should account for the effects of tributary flow even though temperature predictions will be accurate only after the tributary inflow has become fully-mixed in the main flow. If the excess temperature of the river at the point of discharge is assumed equal to the fully-mixed excess temperature, then the decay of river temperature from this point can be analyzed using the "plug flow" analogy. As discussed in Section 3, this analogy is most often considered for long narrow cooling ponds, but is equally applicable to rivers. For such a case, a simple advection surface cooling model will take the form:

$$\frac{\partial(hT)}{\partial t} + \frac{\partial(QT)}{\partial A} + k(T-E) = 0 \tag{3}$$

where T is the water temperature at any time t, as heat is advected through a water body of cumulative surface area A and depth h, at a flow rate Q subjected to surface heat exchange described by the kinematic coefficient of surface heat exchange k $(=K/\rho C)$ and the equilibrium temperature E. The analytical solution to Equation (3) can be found for steady state conditions $(\partial\ (hT)/\partial t = 0)$ assuming that Q, k and E are temporarily constant or averaged over several cycles, and the steady flow Q is given as a function of surface area along the water body as:

$$Q = Q_o + qA \tag{4}$$

where q is an assumed uniformly distributed tributary inflow per unit of water body surface area at temperature T_q. The solution is:

$$T - T* = (T_o - T*)\ [(1 + qA/Q_o)]^{-(1 + \frac{k}{q})} \tag{5}$$

where T* is the approach temperature of the water body given as:

$$T^* = (qT_q + kE)/(q + k) \qquad (6)$$

and T_o is the temperature at the starting point A = 0, e.g. the temperature of a cold water release or the fully-mixed temperature following a thermal discharge. As the tributary inflow rate q approaches zero, Equation (5) converges to the more familiar exponential temperature decay of:

$$T - E = (T_o - E)\, e^{-kA/Q_o} \qquad (7)$$

However, in rivers, q is usually significant along the many kilometers required for the excess heat to be dissipated and is often equal to or greater than k, and Equation (5) should be used. A numerical example, based on the above plug flow analysis, is given in Section 6.

5.5.5 Conditions during winter

The thermal regime of natural rivers is a function of several factors, predominantly the meteorological conditions. During winter, there is a net loss of heat from the water causing ice to form when the surface temperature is sufficiently cooled. Modelling for river temperatures with surface ice cover is lightly different than for summer conditions because of the change in surface heat exchange conditions. An example analysis of surface heat exchange with ice cover has been given by Paily et al (1974a).

When heated discharges from power plants are released into ice-covered rivers, the heat from the discharge helps to melt the ice cover over a certain reach of the river downstream of the outfall. Under these situations, the thermal analysis is the same as that in summer conditions. The length of the river which is ice free can be calculated and an analysis has been presented by Paily et al (1974b). The analysis is similar to that presented in the previous section. A heat balance is maintained betweeen advection, dispersion and heat dissipation to the atmosphere. The latter phenomenon is expressed as a linear function of stream temperature. Under steady state conditions, the temperature at a distance x from the outfall is given by:

$$T(x) = E + T_m \cdot \exp\left[\frac{ux}{2D}\left(1 - \sqrt{1 + \alpha}\right)\right] \qquad (8)$$

where: u = the steam velocity,

D = the longitudinal dispersion coefficient,

α = equivalent to $\frac{4KD}{C\rho h u^2}$,

h = the mean river depth,

T_m = the fully mixed excess temperature (at $x = 0$).

The river is ice free when $T(x)$ is greater than the freezing temperature.

5.5.6 Numerical models

Numerical analysis in thermal modelling is required in situations which are not readily subject to analytical techniques. Several numerical models are available for the prediction of temperature in rivers. However, these models may not be directly applicable in any particular case. A most important aspect of all thermal modelling in rivers is the river hydrology. Some rivers are affected by inflows from tributaries, and the routing of inflows in rivers forms an important aspect of the modelling.

The basic heat transport equation in numerical modelling can be written in the form:

$$\frac{\partial T}{\partial t} + U\frac{\partial T}{\partial X} - D\frac{\partial^2 T}{\partial X^2} + K\,(T - E) = Ha \qquad (9)$$

(temperature variation with time)	(advective heat transport)	(diffusive heat transport)	(heat exchange with the atmosphere)	(heat source term)

The choice of the different terms will vary with the assumptions inherent to the different models. For any model, an input requirement at the upstream boundary will be the completely-mixed temperature, θ_m, which is determined from Equation (1). The models discussed in this section are: Water Resources Engineers Model (1968), U.S. FWPCA Model (Yearsley, 1969), Hydrocomp Model (Hydrocomp, 1972) and COLHEAT Model (Battelle, 1965). Both explicit and implicit numerical schemes are considered in representing the differential equation in the finite difference form.

The Water Resource Engineers model uses the equations of motion and continuity to solve for current velocity and the tidal stage. The river is divided into a set of idealized channels, and velocities and heads are averaged over a short time period and used as input to a stepwise solution of the heat transport Equation (8). The surface heat exchange is expressed by the equilibrium temperature method. Low velocity rivers can be modelled efficiently since longitudinal dispersion is taken into consideration.

The WRE model has not been used frequently for temperature predictions in rivers. The U.S. Army Corps of Engineers (North Pacific Division) have used the WRE model on the Clear Water River but their experience indicates that the model did not perform as expected because the hydraulics of the river were not well simulated by the model (Legg, 1976).

The Hydrocomp model, as indicated in Section 4, is a composite model which deals with the simulation of temperature and water quality in impoundments and rivers. The model takes into account rainfall-runoff considerations and the flows are routed through the different channel reaches and impoundments. However, it is possible to use separately that part of the model which deals with temperature simulations. The river model assumes the river system be divided into uniform channels in which the effects of longitudinal dispersion are neglected. Heat transport by advection and surface heat exchange are considered separately and the flow-discharge relation is obtained using a stream routing technique.

The Hydrocomp model has been used in the Denver region to simulate temperature and water quality in the South Platte River where problems are mainly associated with low river flows. The simulation covered an area of about 400-500 square miles, with a total river reach of about 25 miles containing two power plants. In this case, the simulation of diurnal variations of temperature in the river was within about 5% of the actual temperatures (Hibbert, 1976).

Another study which made use of the Hydrocomp model was the study on land use, flood control and pollution control in the Menomonee River Basin in Wisconsin. The total area of the river basin is about 136 square miles with a mean annual flow of 90 cfs. The only power plant in the basin is the Valley Plant situated near the outlet of the river. Hydraulically and hydrologically, the model presented excellent results, and diurnal variation of temperature and concentrations of other water quality parameters were reproduced with an accuracy similar to the S. Platte study (Walesh, 1976).

The U.S. Water Pollution Control Administration model represents the stream as a series of one-dimensional elements. Longitudinal dispersion is neglected and the surface heat exchange is expressed as a linear or parabolic function of the water temperature. The meteorological variables are supplied to the model input data. This model is best used for rivers which are regulated by dams with small storage capacity. This model may not be applicable for rivers which have very low flow velocities. Also, the model will not be sensitive to varying meteorological conditions.

The COLHEAT model was developed by Battelle, Pacific North West Laboratory, for the simulation of the thermal regime in the Columbia River. Since development, the model has been successfully applied to Deerfield River in Massachusetts (Jaske and Snyder, 1967), the Upper Illinois River (Jaske, 1968) and the Upper Mississippi River (Peterson and Jaske, 1968).

Deerfield River is a small stream of 100 to 1500 cfs flowing in north central Massachusetts. This river was modelled by COLHEAT in relation to the location for the Yankee Atomic Electric Power Plant. The results indicated excellent modelling capability of COLHEAT under extreme regulations of the river.

In the Illinois River, the approximately 278 mile stretch between the Dresden nuclear site and the mouth of the river at Mississippi was considered. This particular stretch of the river has a varying hydraulic regime of canals, swamps and impoundments, three dams, the Dresden reactor plant, and six other thermal power plants, which all discharge heat to the river. Though problems were encountered in the simulation because of the varying hydraulic regime of the river, the model was capable of projecting significant modification of the entire river system downstream of the Dresden plant to the Mississippi.

The study on the Mississippi River also indicated that the COLHEAT river model is widely applicable to the simulation of regional power development systems. In this case, the simulations were carried out on several river tributaries to the Upper Mississippi River and the Mississippi River itself (Figure 33).

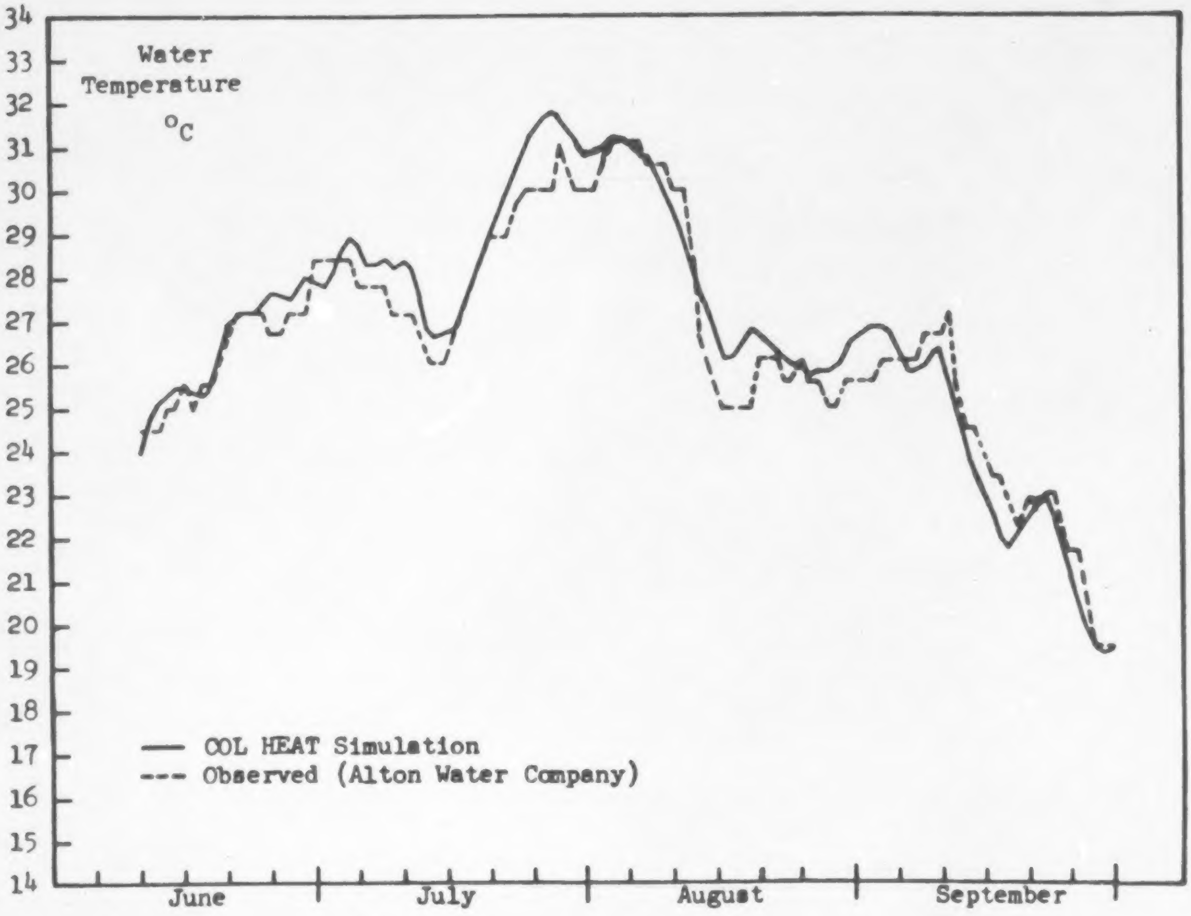

FIGURE 33. MISSISSIPPI RIVER AT ALTON - COMPARISON OF 1964 MEASURED AND COMPUTED TEMPERATURES

The model has also been applied in several other river studies with comparable results. For the Minnesota River and St. Croix River simulations, a minor influence groundwater flow was suspected. However, the differences between the simulated values and the measured values are small. In the case of the Chippewa River the river reach was below the groundwater table and an inflow of groundwater into the channel was included in the model. Even with this modification, the model gave very good comparison with the measured values (Figure 34). These examples compare measured and simulated results, and illustrate the validity and application of the COLHEAT model to different rivers.

A detailed description and flow chart of the COLHEAT program is given by Jaske and Spurgeon (1968). The basic computational system operates on the assumption that most streams are turbulent or supercritical in hydraulic characteristics and the distribution of velocity within the stream is similar regardless of the stream dimensions. The river is divided into three longitudinal troughs, two outer ones and one middle one, and the basic difference equation which predicts the temperature is:

$$T_{i+1,j+1} = (1-B)\,(T_{i,j} + \Delta T^{(1)}_{k,j} + \Delta T^{(2)}_{i,j}) + B\,(T_{i,j-1} + \Delta T^{(1)}_{i,j-1} + \Delta T^{(2)}_{i,j}) \qquad (10)$$

where: $T_{i,o}$ = average temperature of water entering the system during the i^{th} time interval, ^oC,

$T_{i,j}$ = average water temperature of the beginning of the j^{th} flow increment at the end of the i^{th} time increment (flow day) ^oC,

$\Delta T^{(1)}_{i,j}$ = the temperature change during the first half of the i^{th} time interval in the j^{th} flow increment as determined from surface heat exchange plus advected energy (heat budget) in ^oC

$\Delta T^{(2)}_{i,j}$ = same as above except for the second half of the i^{th} time interval, in ^oC,

B = the fractional part of the water in the inner fast moving trough.

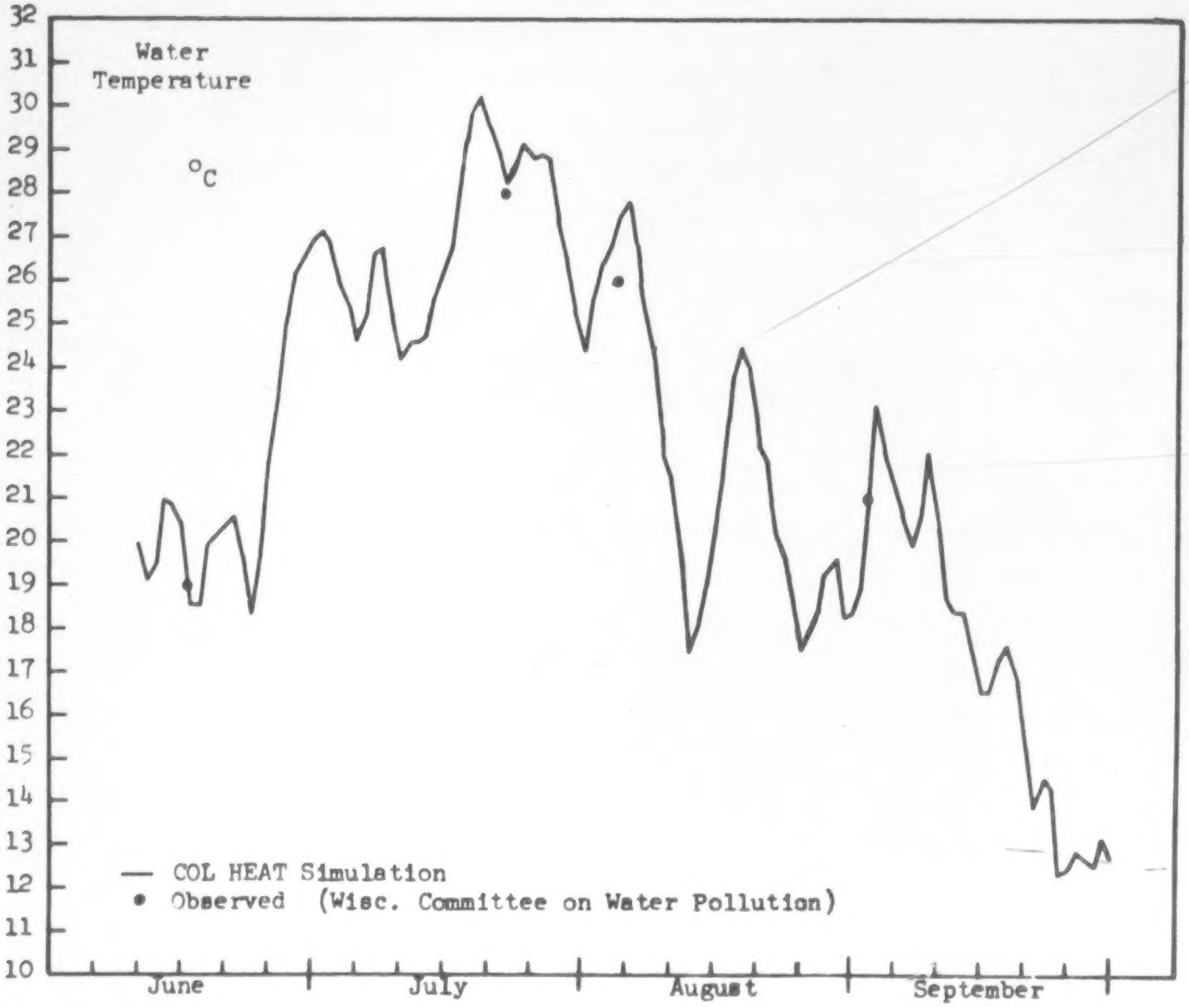

FIGURE 34. CHIPPEWA RIVER AT PEPIN - COMPARISON OF 1964 MEASURED AND COMPUTED TEMPERATURES

The input data required for the operation of the model are:

i) inlet water temperature and outlet flow rate;

ii) meteorological data such as wind velocity for time periods, mean air temperature, dew point, sky cover, and short wave radiation;

iii) river dimensions reduced to equivalent nonparallel trapezoidal cross-sections; and,

iv) advected heat due to thermal discharge.

The input temperature records are not always required for the proper functioning of the COLHEAT model as they are used primarily to facilitate convergence of the finite difference equations. Although the COLHEAT program is being updated and modified, the program and a user's manual are available at the offices of Battelle Pacific Northwest Laboratories and the Atomic Energy Commission, U.S.

In general, however, any of the models described above is applicable in situations in which the rivers can be considered one-dimensionally. However, caution should be exercised in each case since a direct application of an already existing model to a different river system can lead to problems due to the complexity of the individual physical situation and the assumptions used in the numerical models. When considering individual cases, it is usually possible to develop a "new" model which can be based on any of the river models described above and which will be directly applicable to that situation.

As seen above, however, the COLHEAT model is possibly the most widely accepted existing model for use in rivers (and some river reservoirs which are long and narrow). This model is recommended because it is considered to be the most comprehensive of the models described in this section for the prediction of temperature in rivers.

6. SCREENING ALTERNATIVES FOR WASTE HEAT DISPOSAL IN SMALL WATER BODIES AND RIVERS

6.1 Introduction

Previous chapters have considered the general, technical and environmental problems related to waste heat disposal, and have given examples and descriptions of studies for the three main categories considered in this report.

The selection of a waste heat management alternative for these water bodies generally involves two stages:

1) Screening studies in which several cooling alternatives or alternative sites are compared in order to assess the technical-environmental acceptance of a given system on a receiving water body. The collection of data and sophistication of the studies carried out in this stage is generally limited.
2) Detailed studies in which one or a number of alternatives are examined in depth on the basis of a more extensive study program. Once the site has been selected, the content and requirements for detailed studies will be defined with the help of the environmental agencies.

The scope of this particular section is to discuss a step-by-step procedure for the analysis of alternatives at the screening stage (1) of studies, as this is possibly the most difficult stage. In addition, simplified design aids for these preliminary studies are provided and examples of matrices and checklists supplied for the comparison of alternatives. The numerical examples are also based on a review of proposed future steam station sizes.

The range of steam electric generation units considered for this study has been selected on the assumption that future expansion by conventional fossil fuel stations will be comprised of units which vary in size from 100 MW to 500 MW. The smaller units are considered for new semiprivate company operations whereas the larger fossil units, in the 300-500 MW range, are more popular for provincial electrical utilities.

For example, unit sizes of 300 MW will be installed at the 1200 MW Poplar River project; multiple units of 375 MW will go on-line at the Sundance station, and 500 MW units are proposed at the Hat Creek project in British Columbia. Multiple units are standard at most sites, but generally the fossil stations proposed for sites on small water bodies or rivers are not expected to exceed about 2000 MW total.

Candu nuclear units are presently available "off-the-shelf" in 600- and 750-MW capacities. In the 1980's, single units of 1200 MW will be available and a step-up to 1800 MW units is being considered. All of the stations proposed for inland sites near small water bodies will likely be single-unit developments in the 600 MW to 800 MW range. The future units proposed for Manitoba and on the St. Lawrence will 600 MW.

Considering then the size of future steam expansion to consist of these generation categories, the stages in the screening process are indicated in the block diagram, Figure 35. The following sections discuss in more detail how environmental considerations can be incorporated into the procedure for preliminary analysis.

6.1.1 Preliminary data collection

At the time that the type of generation and optimal combination of the above-mentioned units is being selected for each station, decisions are also being taken as to the available sites for development. The proposed operating policy of the station, and other preliminary plant data such as the condenser temperature rise, ΔT, the heat rejection rate, R_p, the cooling water intake temperature, T_i, and condenser flow rate, Q, are all developed at this preliminary stage. This preliminary data acquisition also involves a circular reiteration process essentially related to the selected condenser temperature rise. The value of the condenser temperature rise, the plant pumping rate, and the plant size are related by the formula:

$$P = \frac{2.25 \times 10^5}{R_p} \cdot Q \cdot \Delta T \qquad (1)$$

where P is the plant capacity in MW(e), R_p is the heat rejection rate in Btu per MW hr, Q is the pumping rate in cfs, and ΔT is the condenser temperature rise in $^{\circ}$F.

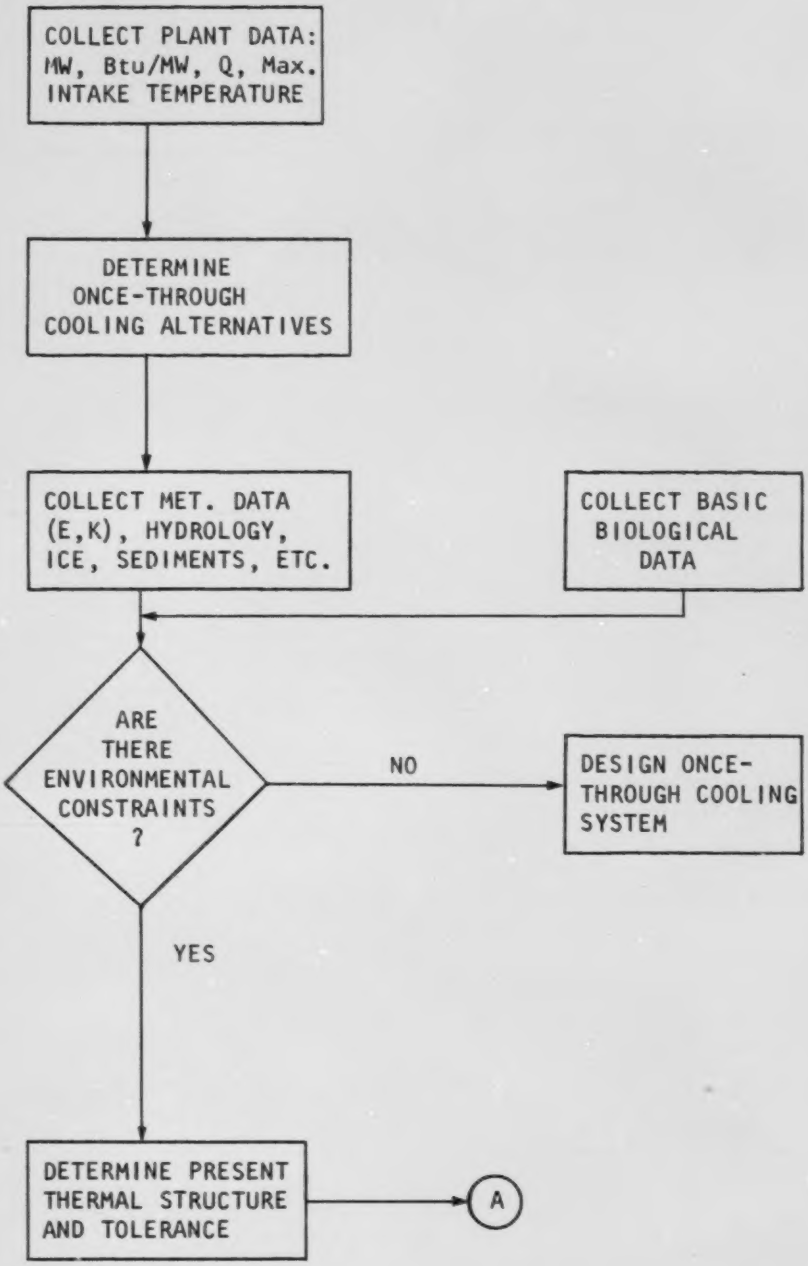
COLLECT PLANT DATA: MW, Btu/MW, Q, Max. INTAKE TEMPERATURE
DETERMINE ONCE-THROUGH COOLING ALTERNATIVES
COLLECT MET. DATA (E,K), HYDROLOGY, ICE, SEDIMENTS, ETC.
COLLECT BASIC BIOLOGICAL DATA
ARE THERE ENVIRONMENTAL CONSTRAINTS ?
NO
DESIGN ONCE-THROUGH COOLING SYSTEM
YES
DETERMINE PRESENT THERMAL STRUCTURE AND TOLERANCE
A

FIGURE 35. SCREENING ALTERNATIVES FOR WASTE HEAT MANAGEMENT IN SMALL WATER BODIES

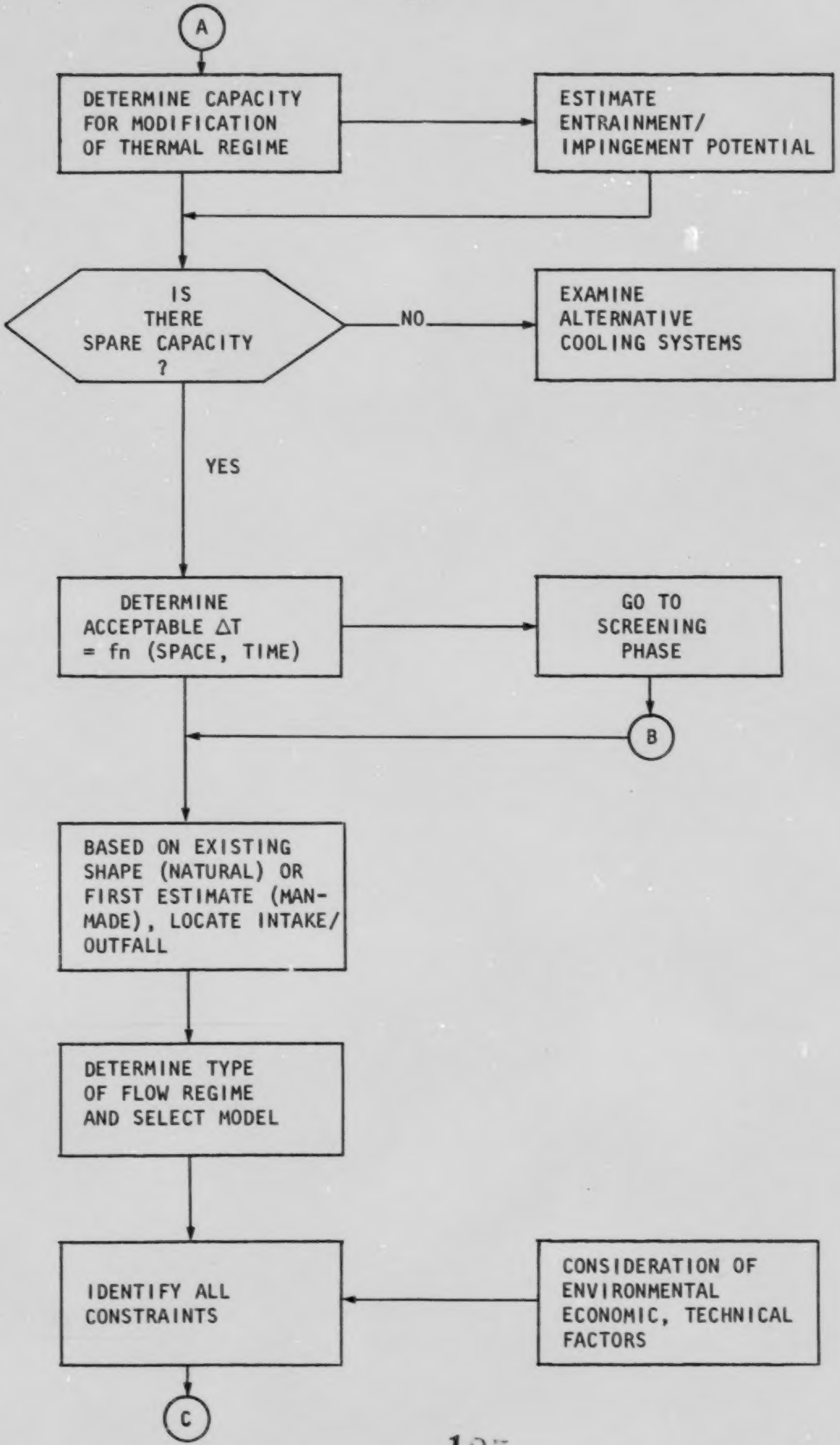
A
DETERMINE CAPACITY FOR MODIFICATION OF THERMAL REGIME
ESTIMATE ENTRAINMENT/ IMPINGEMENT POTENTIAL
IS THERE SPARE CAPACITY ?
NO
EXAMINE ALTERNATIVE COOLING SYSTEMS
YES
DETERMINE ACCEPTABLE ΔT = fn (SPACE, TIME)
GO TO SCREENING PHASE
B
BASED ON EXISTING SHAPE (NATURAL) OR FIRST ESTIMATE (MAN-MADE), LOCATE INTAKE/ OUTFALL
DETERMINE TYPE OF FLOW REGIME AND SELECT MODEL
IDENTIFY ALL CONSTRAINTS
CONSIDERATION OF ENVIRONMENTAL ECONOMIC, TECHNICAL FACTORS
C

FIGURE 35. (CONT'D)

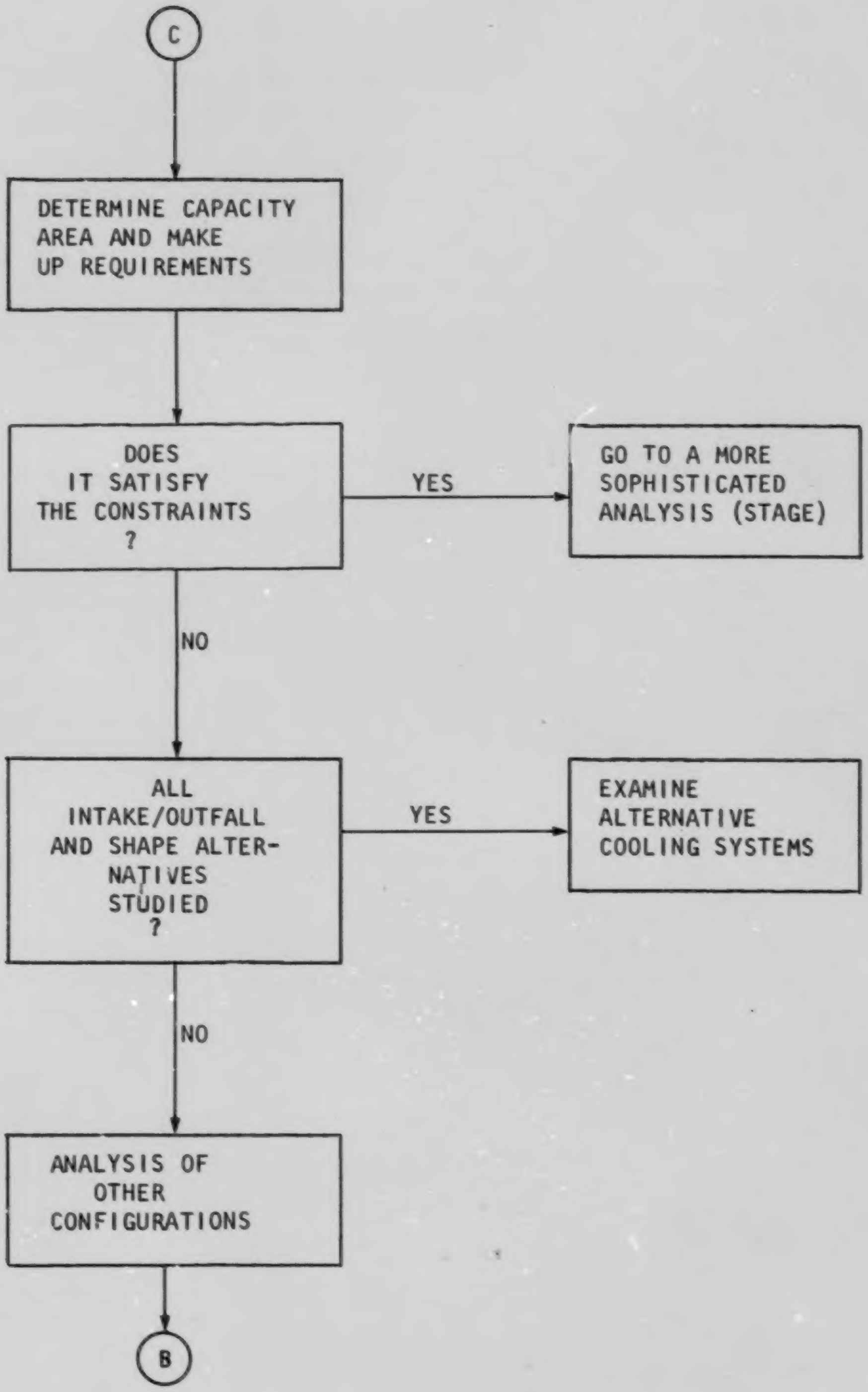
C
DETERMINE CAPACITY AREA AND MAKE UP REQUIREMENTS
DOES IT SATISFY THE CONSTRAINTS ?
YES
GO TO A MORE SOPHISTICATED ANALYSIS (STAGE)
NO
ALL INTAKE/OUTFALL AND SHAPE ALTERNATIVES STUDIED ?
YES
EXAMINE ALTERNATIVE COOLING SYSTEMS
NO
ANALYSIS OF OTHER CONFIGURATIONS
B

FIGURE 35. (CONT'D)

The waste heat discharged from these steam-electric plants also varies with the efficiency of the steam generation cycle. With fossil fuel plants, the stack and miscellaneous losses typically amount to about 15 percent of the input energy. Thus, the heat rejected to the cooling water is approximately 3900 Btu/kw-hr and the overall thermal efficiency is about 40 percent. On the other hand, the CANDU reactor releases about 7580 Btu/kw-hr and operates at about 30 percent thermal efficiency.

Considering then the range of typical steam generation units, Figure 36 summarizes the condenser cooling flow required for typical condenser temperature rises. In general, the relationship between the condenser temperature, rise, the pumping rate, and the potential outfall mixing should be agreed upon between the utility and the environmental agencies.

At the screening stage, all of the possible cooling system alterernatives must be examined and the constraints on their use determined. It is also suggested that the importance of environmental constraints be established from the very first stage of the analysis. Consequently, as the selected sites are known, it is important to determine whether the aquatic environment is to be assessed as a sensitive consideration or constraint in the screening of these alternatives. If the station is proposed at a site that is known to be of minimal environmental concern, such as a man-made cooling pond, then environmental constraints will not enter as a factor and the following preliminary receiving water body collection phase will only be required to determine technical parameters on the cooling system. This collection phase will result in design information related to the hydrologic regime, ice conditions, sediments, meteorology, water body bathymetry and geometry, and potential recirculation.

Approximate surface cooling coefficients, K, and equilibrium temperatures, E, would be computed from existing meteorological data relating to the thermal structure of the receiving body.

If environmental aspects are expected to be important at the selected sites, additional preliminary information will be required in the receiving water body data collection phase. Preliminary aquatic biological data will be required to determine the limits for modification

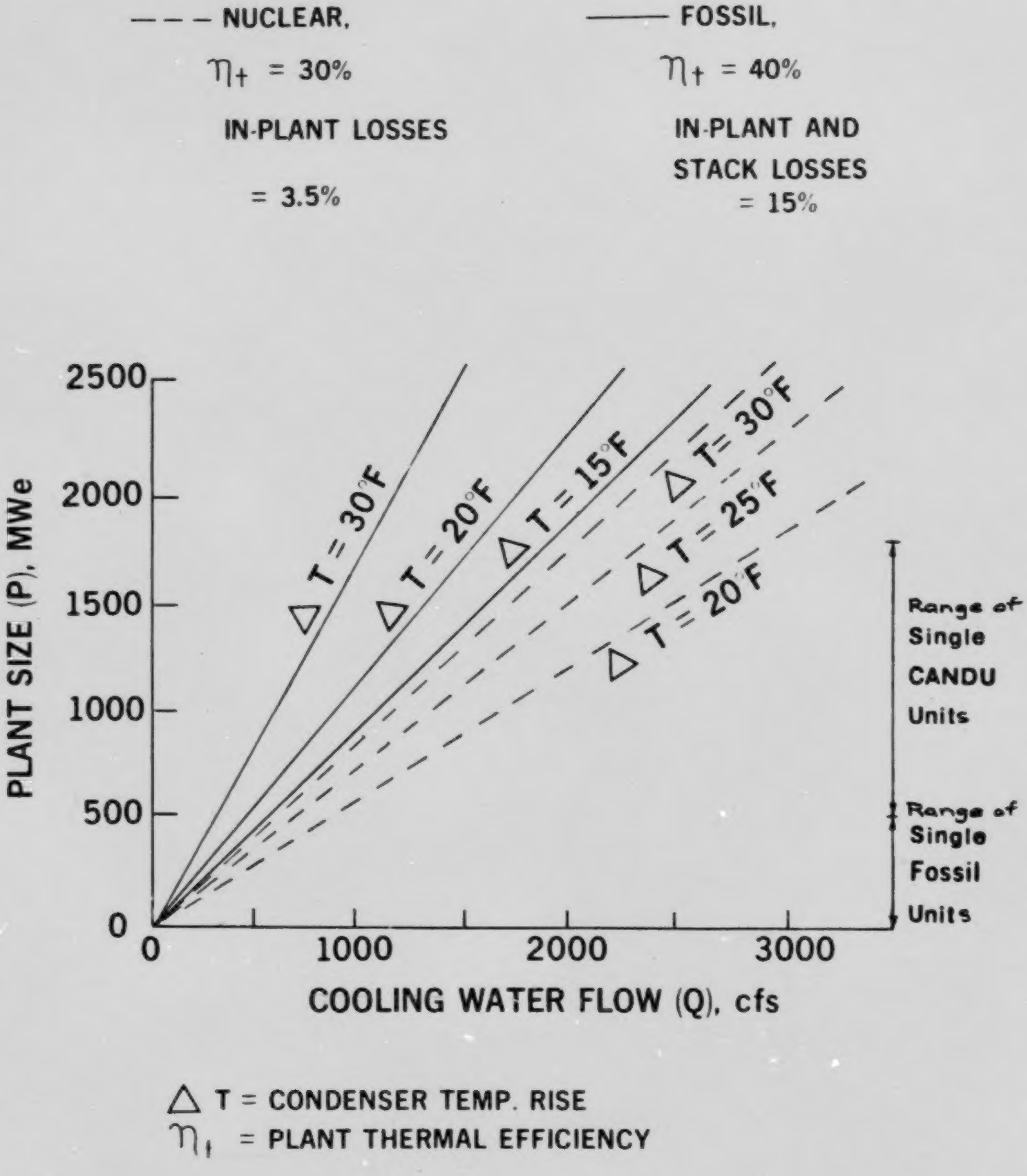

FIGURE 36. COOLING WATER REQUIREMENTS FOR FOSSIL AND NUCLEAR POWER PLANTS

of the existing thermal regime. If some capacity for modification is possible without significant environmental damage, these modifications will project into the overall picture some additional constraints to be considered in conjunction with the technical and economic limitations being formed at the same time. If there is no capacity to add additional thermal discharge to a water body because of sensitive or already stressed aquatic communities, other cooling alternatives must be considered, unless a decision is made to proceed on other grounds, e.g. social, political, etc.

The sum of these bio-environmental constraints may be advanced as thermal constraints or nonthermal constraints. The nonthermal aspects relate to mechanical effects such as entrapment and impingement, and to changes in water chemistry, dissolved oxygen or dissolved solids. The thermal constraints may appear as limitations on the mode of discharge, the spatial or seasonal distribution of the heated discharge or the allowable changes in life-cycle response. The thermal and nonthermal limitations are usually very closely related, and for purposes of preliminary analysis can be summarized as thermal constraints. For example, a change in impingement mortality may result from a reduction in cooling water flow, which in turn implies an increase in the cooling water temperatures.

In summary, the preliminary data collection phase will bring together basic plant information and background water body information to form a series of constraints for each site. The amount of information to be collected in order to reach acceptable decisions cannot be easily defined, however, since the quality of input data influences the reliability of the conclusions. The designers and decision-makers are thus required to rely on the experience and judgment of the analyst.

In some situations, assessment of alternatives which would have to be considered at some advanced stages may be preliminarily assessed at the screening phase. For example, preliminary intake and outfall alternatives must be advanced because their interaction will in part define the hydrothermal regime of the water body. Once the shape and regime are defined, a suitable hydrothermal modelling approach can be selected, and preliminary simulations will provide the first estimates of surface areas required for cooling, circulation pattern, water body temperature variations, etc.

If there are no biological constraints, these estimates will enable comparison of all available cooling system and intake-outfall alternatives based strictly on technical, economic, and other environmental constraints. If the preliminary alternative fails to satisfy these constraints, then another alternative intake-outfall location or cooling system can be tested at the site. The introduction of biological constraints does not change this procedure because they are translated into physical limitations, such as temperature increases, similar to those for the technical analysis.

In the following sections, several preliminary design aids and examples are presented to indicate the level of analysis required for preliminary screening of cooling alternatives on small water bodies and rivers. Present and possible future environmental legislation, biological and operational rules of thumb, typical Canadian conditions, and simple mathematical modelling have been combined in this approach. Although there is certainly no substitute for a case-by-case evaluation of each cooling mode at each site, it is felt that the following approach can be adopted in most instances to indicate the most promising preliminary alternatives for future detailed studies.

6.2 Preliminary Analysis for Shallow Water Bodies

6.2.1 Simplified hydrothermal considerations

As indicated in Section 3, a shallow water body may be considered to fall within the fully-mixed or plug flow categories of analysis (Figures 7 and 9). The shape of the water body and the relationship between the preliminary intake and outfall alternatives will assist in this categorization by indicating recirculating or once-through flow regimes. The mathematical relationships indicated in Section 3 can then be used to develop simplified tables and diagrams which, as explained in the following sections, may be useful in the initial screening assessment of waste heat disposal alternatives.

6.2.2 Recirculating shallow fully-mixed ponds

Fairly regular, shallow, fully-mixed, recirculating ponds will reach a temperature excess at which the rate of surface heat dissipation balances the rate of plant heat rejection (Section 3).

The equilibrium temperature in a shallow recirculating pond will be fairly close to the natural water temperature for much of the year. The temperature excess above the equilibrium temperature, at which no heat transfer across the water surface takes place, may be written:

$$\theta = R_p G_e / KA \tag{2}$$

where: θ = fully mixed temperature rise ($^\circ$F),
R_p = heat rejection rate of plant (Btu/hr/MW),
G_e = power generation (MW),
K = surface exchange coefficient (Btu/day/ft^2/$^\circ$F),
A = pond surface area (ft^2).

The surface heat exchange coefficient, K (discussed in Section 3) is representative of local meteorological conditions, in particular of average wind speed, humidity and air temperature. R_p depends on the type of plant, nuclear or fossil, and its efficiency. It is important to note that the pond is assumed to be at one temperature; this is also the intake temperature in a closed-cycle pond.

Figure 37, which is a generalized solution to Equation (2), can be used in this preliminary screening as it combines both nuclear and fossil heat rejection rates with various meteorological conditions (typical seasonal K values). The figure illustrates, for example, that a 750 MW steam station on a 1000-acre pond will raise the average pond temperature by 11.5°F (6.4°C) during the summer, whereas the temperature rise from a 750 MW nuclear unit would correspond to about 22.5°F (12.5°C).

In the instance that the pond is a man-made body, or a shallow body not considered to be of biological importance, the fully-mixed temperature rise (intake temperature) is only constrained by the most efficient condenser operations. The required pond-size, or conversely,

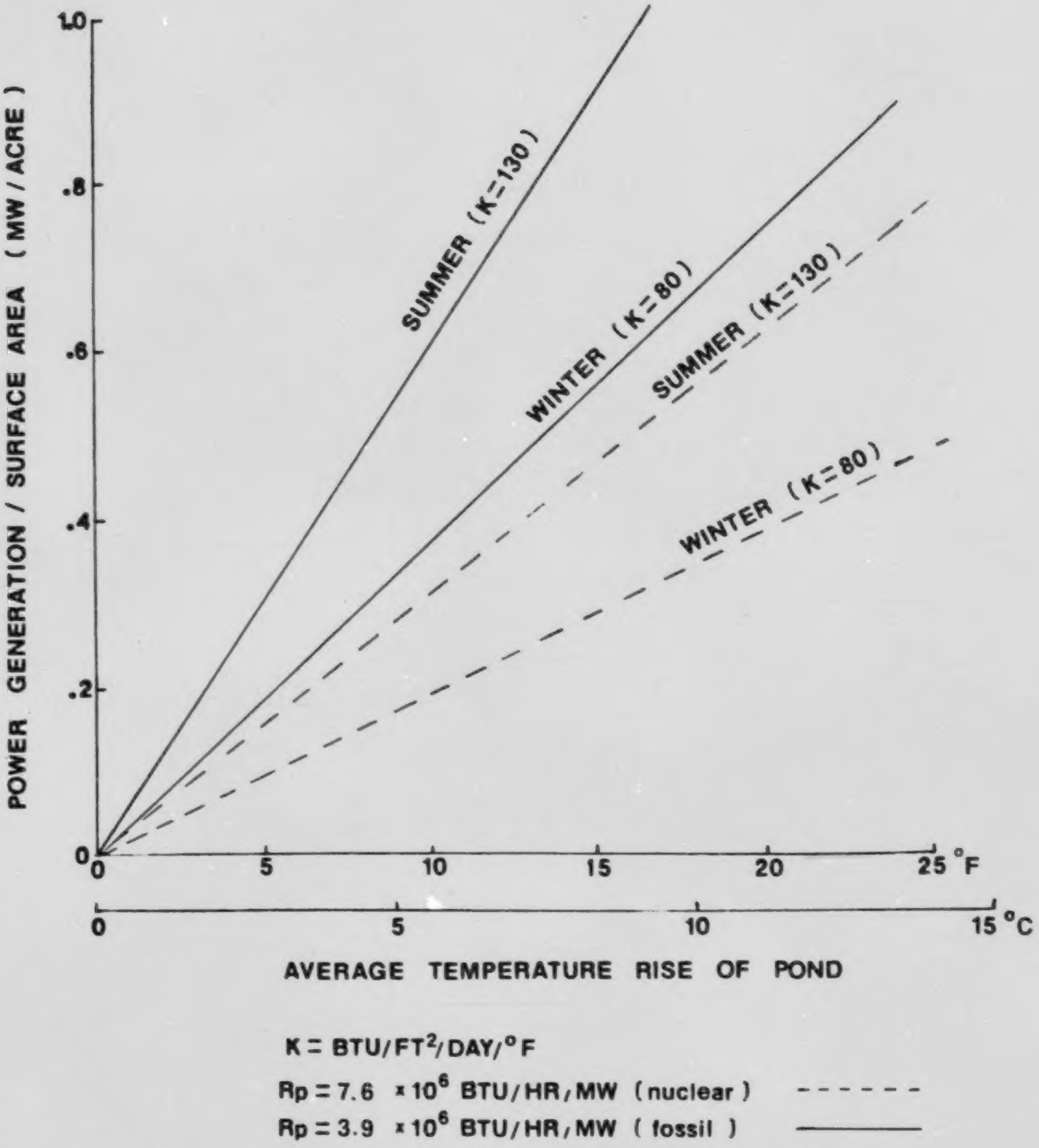

FIGURE 37. AVERAGE TEMPERATURE RISE OF A FULLY-MIXED POND

the effect of adding a plant on a proposed or existing pond configuration, can thus be simply determined on the basis of the plant data base alone. If there are biological temperature restrictions on the temperature rise, the procedure will be the same as for the technical analysis.

6.2.3 Once-through shallow fully-mixed ponds

In the instance that the outfall portion of the receiving body is separated from the intake portion, so far as potential recirculation is concerned, the fully-mixed temperature rise of the pond may be expressed as:

$$\theta = R_p G_e/(KA - Q\rho C_p) \qquad (3)$$

where Rp, G_e, K and A are defined as above (Equation 2), Q is the condenser (cooling water) flow rate in cfs, ρ is the density of water in lb/ft^3, and C_p is the specific heat of water and is equal to 1 Btu/lb/°F.

Figure 38 is a graphical solution to this formulation for a 750 MW nuclear power plant having a condenser temperature rise of 25°F (13.9°C) and an assumed cooling flow rate of 1110 cfs. Similar curves can also be constructed for any size of plant or for different flow rates. Figure 38 shows, for example, that the average temperature rise of a 1000-acre pond will be 13.5°F (7.5°C) in the summer and 21°F (11.7°C) in the winter season. The figure also demonstrates the nature of the increase in pond temperature with decreasing pond size (power generation per surface area).

Comparison of Figures 37 and 38 indicates that, for a 750 MW nuclear unit, the temperature rise in the recirculated fully-mixed pond would be almost twice that of the flow-through case (22.5°F vs 13.5°F). To obtain the same outlet temperature, the recirculated pond would be required to be about twice the size of a fully-mixed flow-through pond.

6.2.4 FLow-through plug flow ponds

For the preliminary analysis of flow-through plug flow ponds, such as elongated natural or man-made helper cooling ponds that are shallow (Figure 39), the difference between the intake temperature and the temperature at the outlet from the pond may be written:

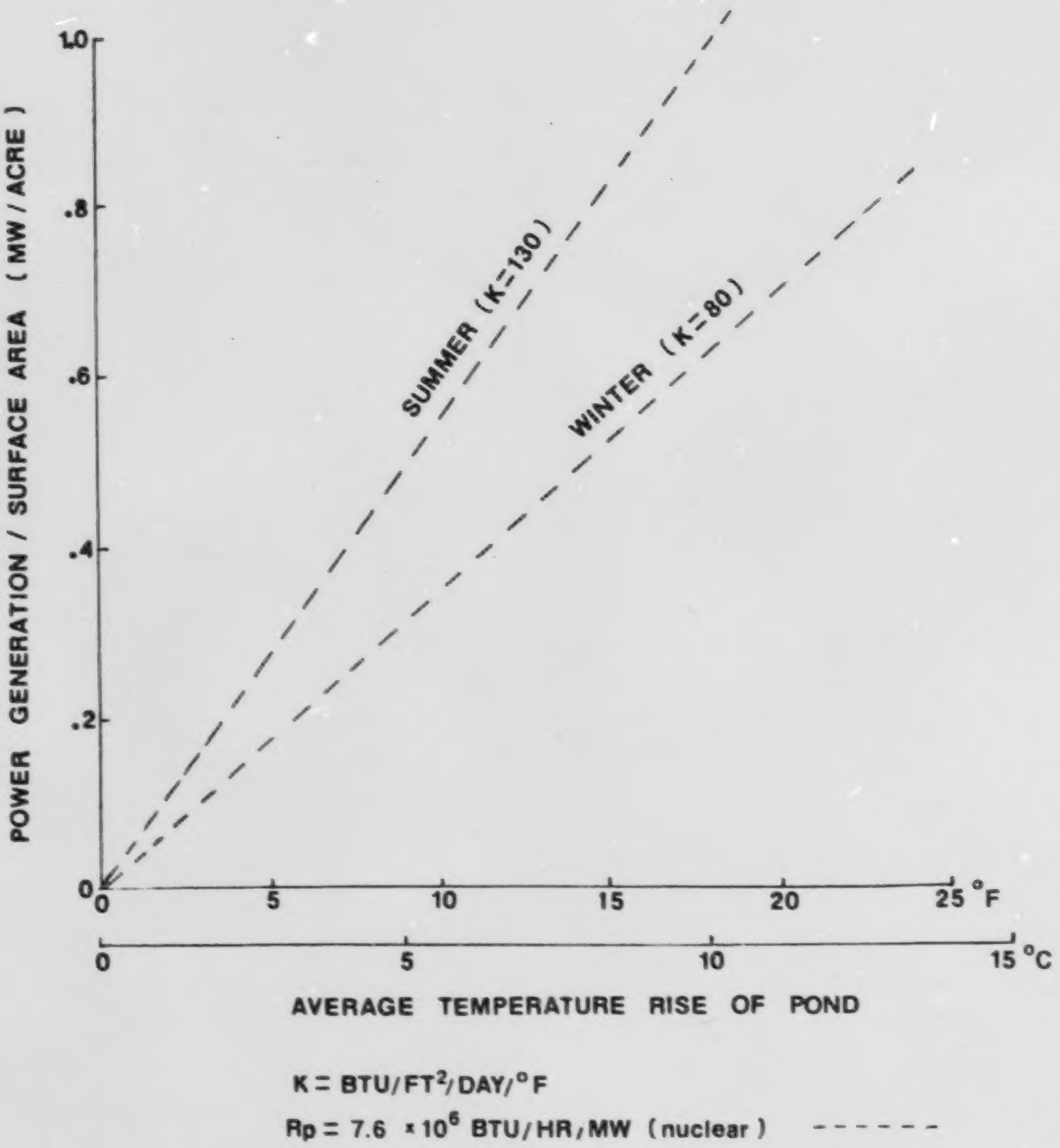

FIGURE 38. AVERAGE TEMPERATURE RISE OF ONCE-THROUGH FULLY-MIXED POND (750 MW Nuclear Plant)

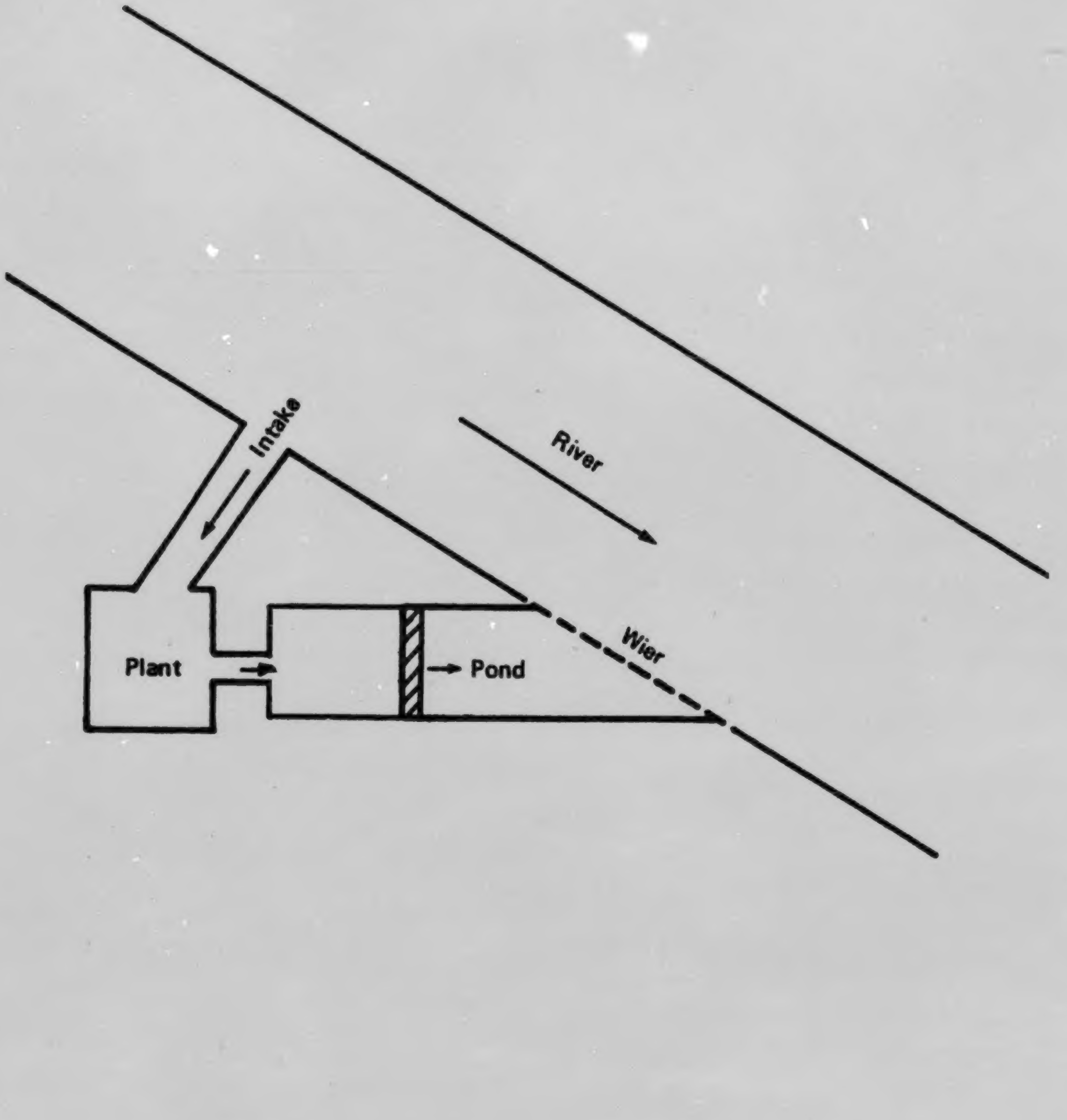

FIGURE 39. FLOW-THROUGH COOLING POND

$$\theta = \frac{R_p Ge}{\rho C p Q} e^{-KA/\rho C_p Q} \tag{4}$$

where all of the variables have been defined above in Equations (2) and (3).

The solution to this equation can be illustrated by a series of curves such as those shown in Figures 40 and 41. These show the variation of the pond discharge excess temperature with cooling water flow rates for fossil and nuclear plants of various size on a 1000-acre pond for average surface cooling conditions. Similar curves may be drawn for other surface areas or for different surface cooling conditions. For example, Figure 42 also applies to a 1000-acre pond and to a number of nuclear units, but it is based on summer surface cooling conditions (K = 130).

The plug flow analysis indicates that the summer temperature excess at the pond outlet would average about $8^{o}F$ ($4.4^{o}C$) for a 750 MW unit. By comparison to the previously discussed once-through fully-mixed pond (Figure 38), the average outlet temperature excess would be about $14^{o}F$ ($7.8^{o}C$). In essence, this comparison illustrates the difference between these two flow analyses. As mentioned in Section 3, most ponds will fall between these two ranges and the selection of the most appropriate value must be approximated on the basis of an appreciation of the geometry and intake-outfall configuration (Figure 14).

It is also important to note that there is practical minimum condenser flow defined by:

$$Q_{MIN} = \frac{R_p Ge}{\rho C_p \Delta T_{max}} \tag{5}$$

where ΔT_{max} is the maximum acceptable condenser temperature rise. Thus, there is a trade-off between pumping requirements and pond discharge temperature. The figures illustrate the possible benefits of avoiding the peaks on these curves to minimize the temperature rise at the pond outlet. This is evidently important if there is a biological constraint on the outflow temperatures but is equally valid if the recirculation potential of the pond is considered.

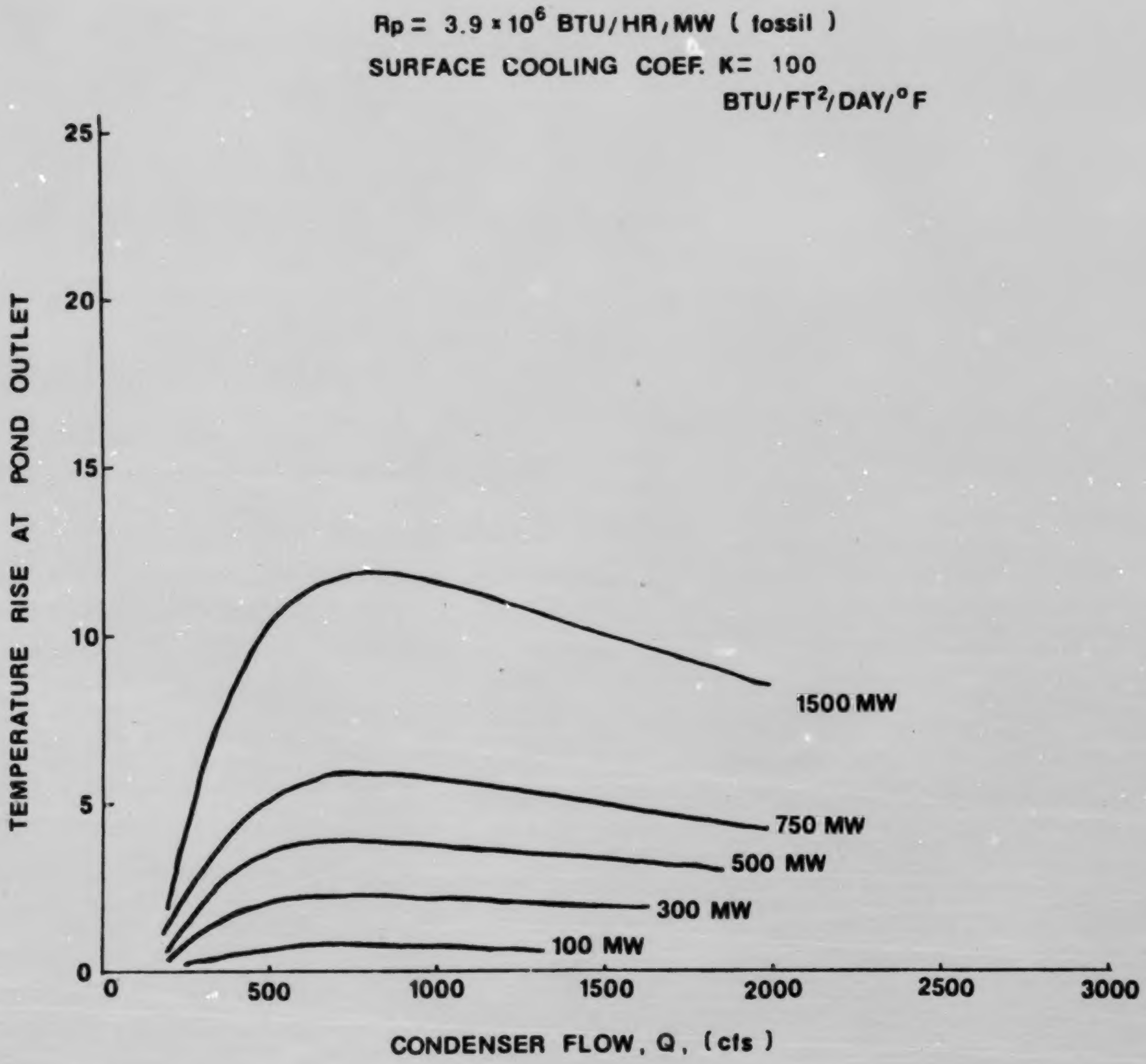

FIGURE 40. EXCESS TEMPERATURE VARIATION OF ONCE-THROUGH PLUG FLOW POND (Surface Area 1000 Acres, Rp = 3.9×10^6 Btu/hr/MW (fossil), K = 100 Btu/ft^2/day/^{o}F)

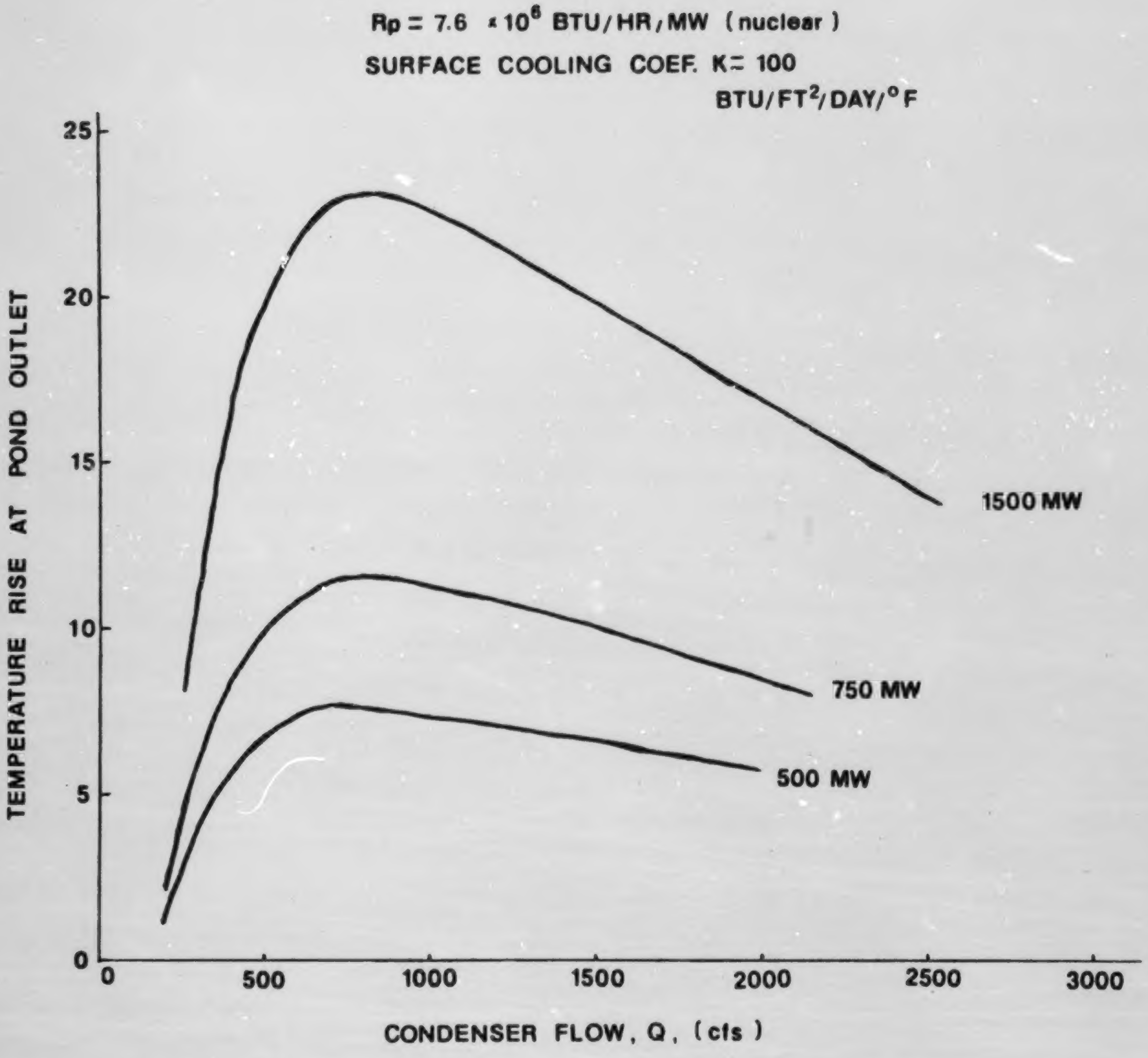

FIGURE 41. EXCESS TEMPERATURE VARIATION OF ONCE-THROUGH PLUG FLOW POND (Surface Area 1000 Acres, Rp = 7.6 x 10^6 Btu/hr/MW (nuclear), K = 100 Btu/ft^2/day/^{O}F)

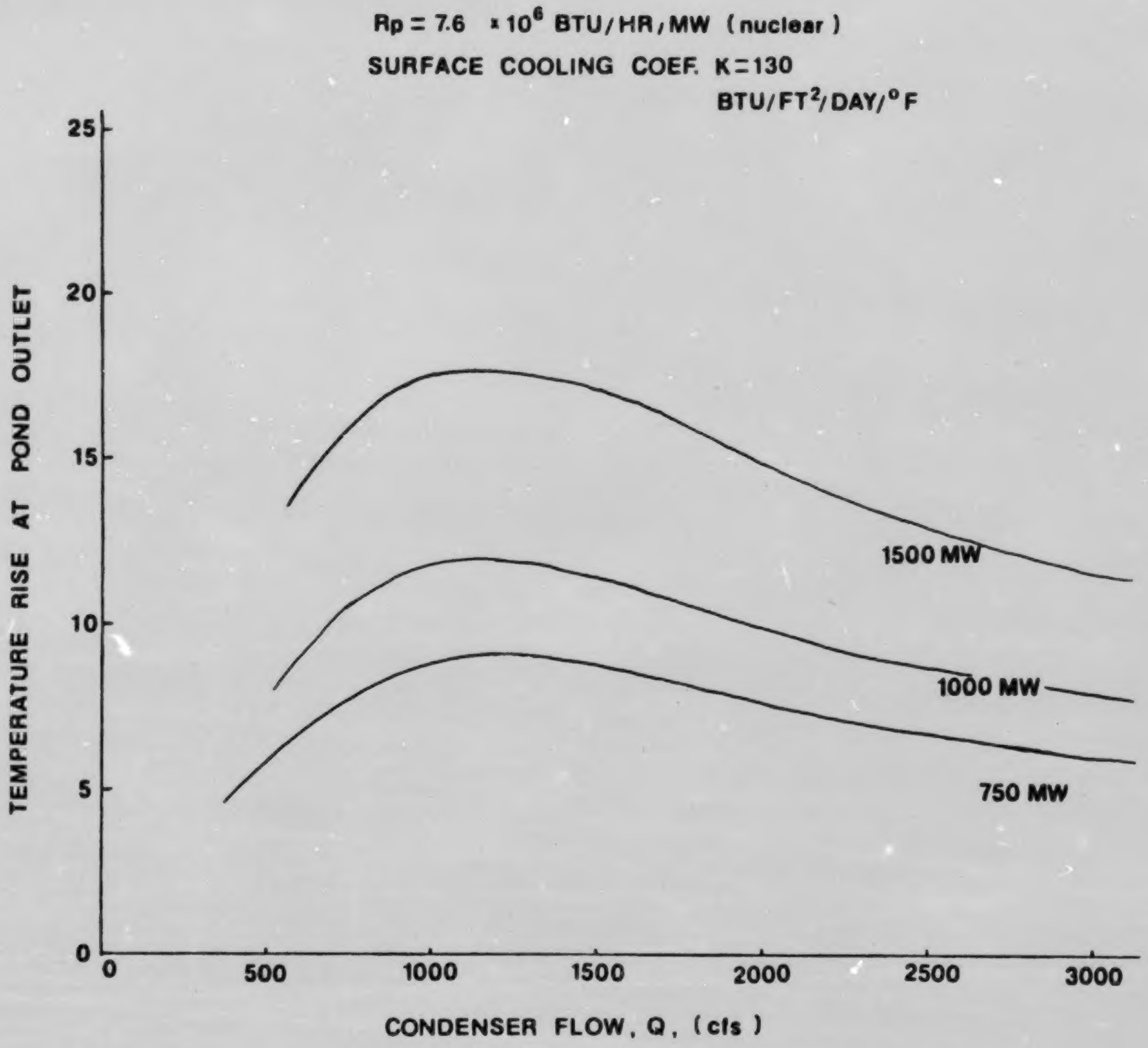

FIGURE 42. EXCESS TEMPERATURE VARIATION OF ONCE-THROUGH PLUG FLOW POND (Surface Area 1000 Acres, Rp = 7.6 x 10^6 BTU/hr/MW (nuclear), K = 130 Btu/ft^2/day/^{o}F)

6.2.5 Recirculating plug flow ponds

In contrast to the flow-through pond, the plug flow analysis can also be applied to elongated shallow water bodies exhibiting recirculation (Figure 43). In this case, the pond outlet temperature, Θ, becomes the intake temperature, T_i. The temperature excess can be considered as the difference between the intake temperature and the equilibrium temperature:

$$(T_i - E) = \Theta = \frac{R_p Ge}{\rho C_p Q} / (e^{KA/\rho C_p Q} - 1) \qquad (6)$$

where all symbols are as defined above. The excess temperature at any point along the pond can be determined by substitution of the appropriate area*.

Figures 44 and 45 illustrate the variations in pond intake (outlet) temperature excess with cooling water flow rates on various sized ponds for a 400 MW fossil-fuel plant and a 750 MW nuclear station at summer surface cooling conditions (K = 130).

Figure 45 indicates that the average temperature excess, for the 750 MW nuclear plant requiring 1500 cfs and located on a 1000 acre pond, would be about 15°F (8.3°C). By comparison, the temperature excess in a fully-mixed pond (Figure 37) would be about 22°F (12.2°C). This points out that the selection of plug flow or fully-mixed analysis, when considering a recirculating shallow body, leads to about the same difference in excess temperatures as in the flow-through case. In both cases, however, the average pond temperature is considered to be the fully-mixed temperature.

6.2.6 Minimum inflow requirement

It is generally concluded that shallow lakes or ponds used as recirculating water bodies will evaporate more cooling water per unit of waste heat dissipated than would be evaporated using a once-through cooling system. Thus, in regions where limited supplies of water are available, and recirculating cooling ponds are considered, the make-up requirements for cooling ponds should be carefully considered.

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* A modified version of this equation may be used for recirculating plug flow ponds with side arms (Section 3).

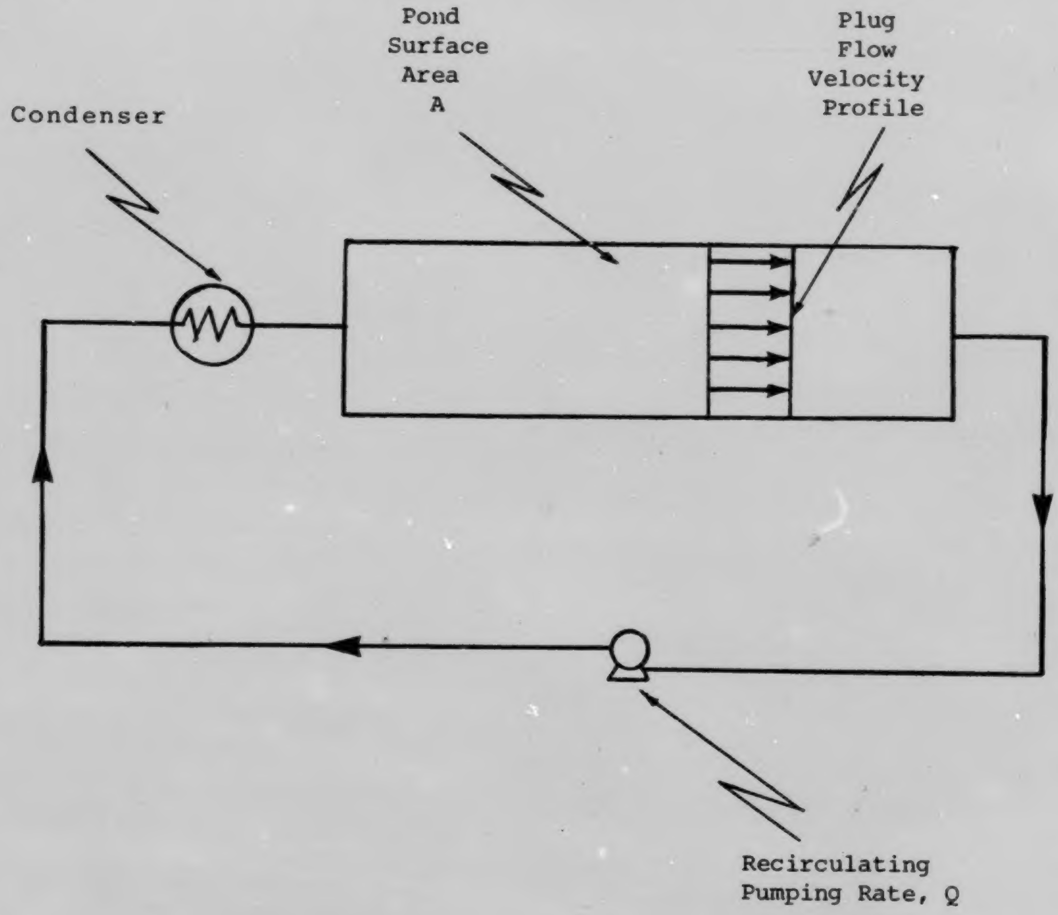


FIGURE 43. ELONGATED SHALLOW WATER BODY - RECIRCULATED PLUG FLOW

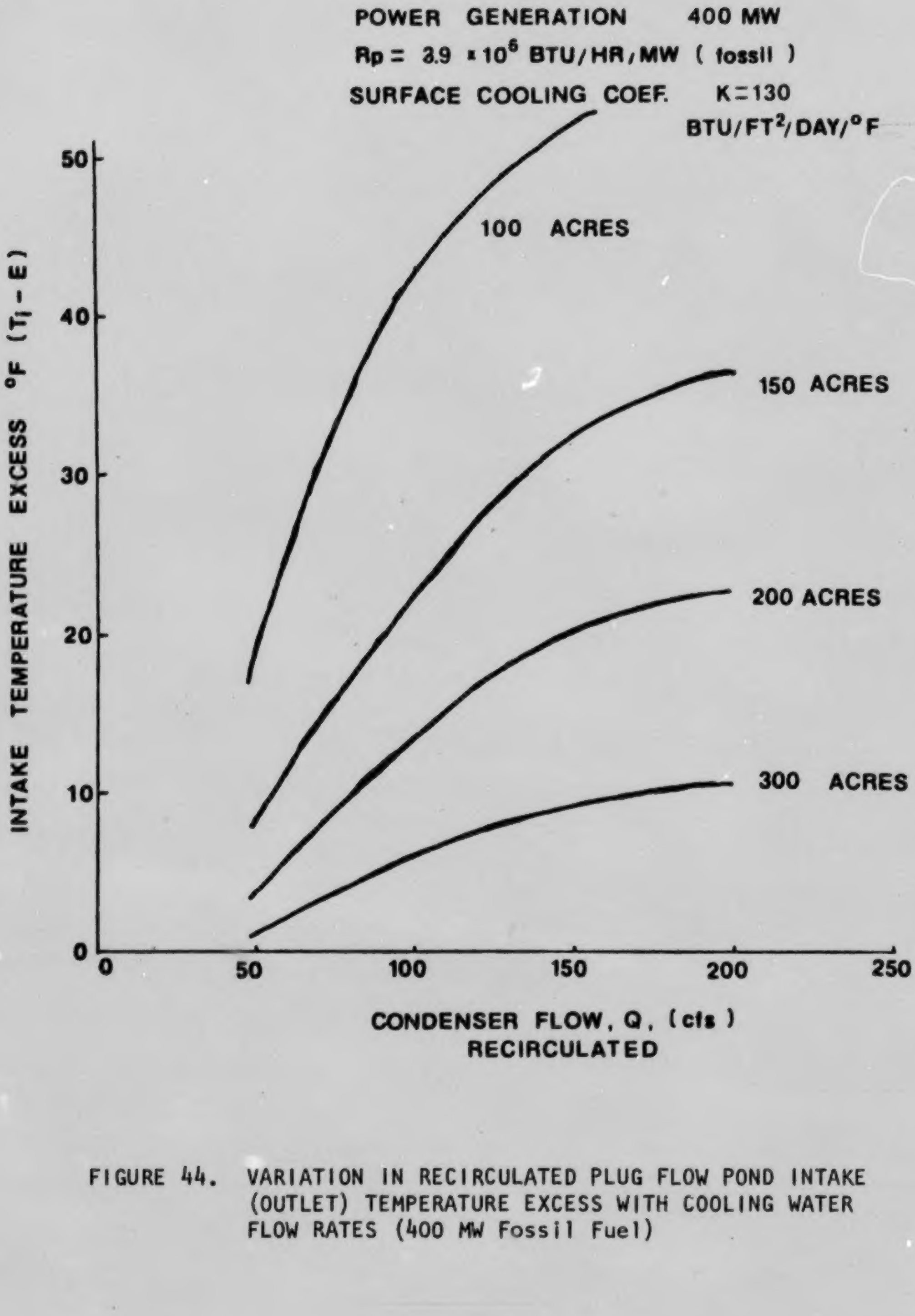


FIGURE 44. VARIATION IN RECIRCULATED PLUG FLOW POND INTAKE (OUTLET) TEMPERATURE EXCESS WITH COOLING WATER FLOW RATES (400 MW Fossil Fuel)

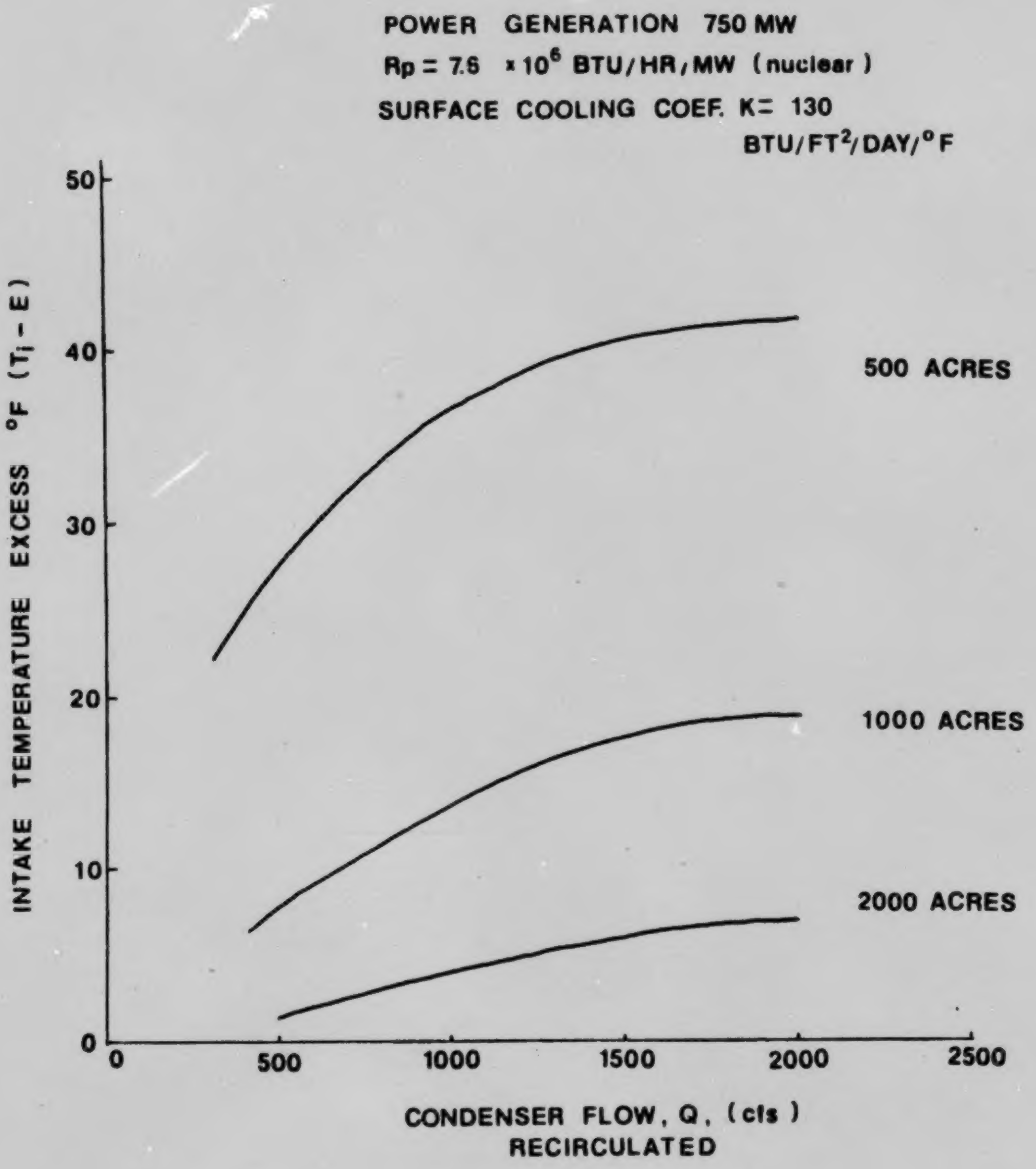


FIGURE 45. VARIATION IN RECIRCULATED PLUG FLOW POND INTAKE (OUTLET) TEMPERATURE EXCESS WITH COOLING WATER FLOW RATES (750 MW Nuclear)

Natural evaporation occurs as a result of the difference in the partial pressure of water in air, at the water surface and in the ambient air. The rate of natural evaporation depends on the dew point, wind speed and surface temperature. When waste heat is added to a cooling lake, there is an increase in the evaporation rate known as forced evaporation.

The consumptive use of water depends on the balance between total evaporation and precipitation. This balance varies seasonally as shown in Figure 46 (for man-made ponds). Sonnichsen (1975) suggests that a maximum consumptive use of water may reach about 0.025 cfs/MW for man-made ponds.

In addition to evaporative losses, make-up requirements for a cooling pond must include blowdown, which is governed by the allowable increase in concentration of solids and chemicals due to water evaporation.

Assuming again average values of evaporation, forced evaporation and blowdown, it may be said that the total make-up requirement for fossil stations averages about 0.03 cfs/MW, and for nuclear stations 0.04 cfs/MW. In general, however, as the natural evaporation and make-up water quality are site specific, it is more advantageous to assess the total make-up requirement on an individual basis.

6.3 Preliminary Input of Biological Constraints

6.3.1 Determination and pre-design

If there are biological constraints on the use of an existing shallow lake, pond, or reservoir for cooling, the preliminary data collection phase at each site will have identified the site-specific biological characteristics of the water body and the capacity of the aquatic population to accept a quantity of heated discharge.

It is understood that no single water body will contain only one species of fish or plant to the exclusion of all others. Therefore, it must be determined initially which species must be designated for protection and what temperature tolerance limits are to be established. Once these temperature limits have been determined by the environmental

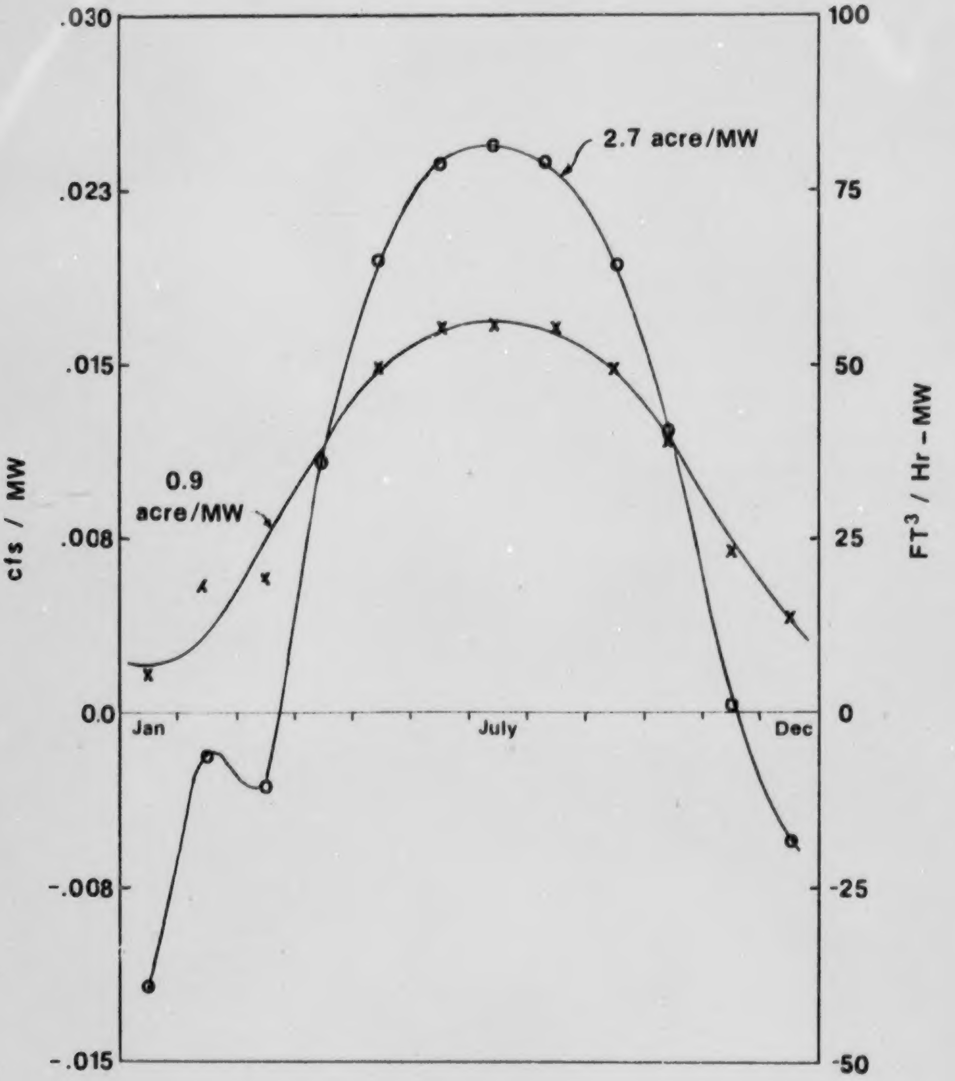


FIGURE 46. CONSUMPTIVE* WATER USE FOR A FULLY-MIXED MAN-MADE POND (FOSSIL FUEL PLANT)

*Areas where precipitation approximately balances natural evaporation.

Adapted from Sonnichsen (1975)

agency, the various thermal criteria can be applied through the same modelling procedure outlined earlier in this section.

During the data collection stage, it may be possible for the environmental agencies to identify the basic character of the pond and, considering the indigenous fish population, for example, define which species are to be protected and the level of thermal protection required. For purposes of the following discussion, it is assumed that the maximum average pond temperatures, Tma, in Canada should not exceed about 20°C for the protection of cold water fish such as Salmonids and Corregonids, and 30°C for warm water fish such as Centrarchids and Ictalurids. Similarly, it is assumed that the average pond temperatures, Θ, should also not be raised above ambient temperatures by more than about 2°C for the cold water species and 3°C for the warm water species. Some intermediate values may also be applied for groups such as Catostomids, Perkids and Esocids if these are designated for protection.

The maximum upper average temperature for the pond (Tma) is the temperature at which the fish genera indicated can best fulfill all of their functions for existence in a complex ecosystem. Functions for which there is an average optimum temperature (below the Tma) include spawning and reproduction, development, feeding and "general competition". If sensitive fish species are adequately protected, then it is likely that the other fundamental components of the ecosystem will be preserved, although a shift in species diversity and abundance might occur for some of the components.

The average chronic increase in the temperature of the entire lake is defined by the symbol Θ. In the instance of a symmetrical water body with a completely mixed regime, this temperature increase will reflected throughout the entire water body. Spawning and egg development stages for fish species in any lake are the most temperature sensitive functions that occur in an aquatic ecosystem. Temperatures at which these events occur are critical and must be held within a relatively narrow range. For example, for coldwater fish, a lake remains at 0°C over the winter and egg development for fall spawners occurs at 0-4°C. Therefore, the addition of 2°C (Θ) to a lake at 0°C ambient temperature will bring the mean temperature to 2°C and should not endanger the egg development of cold water species.

Biological temperature criteria may thus be advanced in the form of three constraints. The initial biological constraint concerns the average temperature rise over the entire water body. The relationship between plant size, and the existing water body area subject to a given biological restriction on the average temperature rise is approximated by using the fully-mixed water body Equations (2) and (3). Figure 47, which is based on the same assumptions as Figure 37, provides another graphical representation of Equation (2) for fully-mixed recirculating water bodies. This particular figure provides somewhat more detail for the lower values of pond temperature rise ($\theta = 2^{\circ}C$ or $3^{\circ}C$), to enable preliminary determination of whether or not a pond of a given size can support a proposed plant and still maintain a biological resource. Considering a 750 MW nuclear plant, for example, the pond size required to limit the average temperature rise of the pond to $2^{\circ}C$ would be 6650 acres. In contrast, if the pond were sized on criteria permitting an average temperature rise of perhaps $10^{\circ}F$, the required pond size would be 1350 acres.

The second possible biological constraint may take the form of limitation on the distribution of temperature within the shallow water body. On practical grounds, allowances must be made for the temperature rise to exceed environmentally acceptable values within only a small area of the lake. Consequently, this second temperature constraint limits the area that can be contained within a particular isotherm. Equations (4) or (6), which are based on the plug flow analogy, can be useful with regard to such limitations. Using a biological restriction on the percentage of the total water body area that must not exceed the environmentally acceptable limits discussed above, and applying Equation (4) will give the relationship between the plant size and the pond size. Table 8 summarizes the pond area required if 5%, 10% and 15% of the pond area is allowed to exceed $3^{\circ}C$.

Two potential problems are associated with heating greater than, for example, 5% of the pond surface area to a temperature $3^{\circ}C$ or more above ambient. Firstly, the spawning areas for fish requiring cold water for egg development might be jeopardized. This is especially likely to occur in the winter months as heated water discharged on the

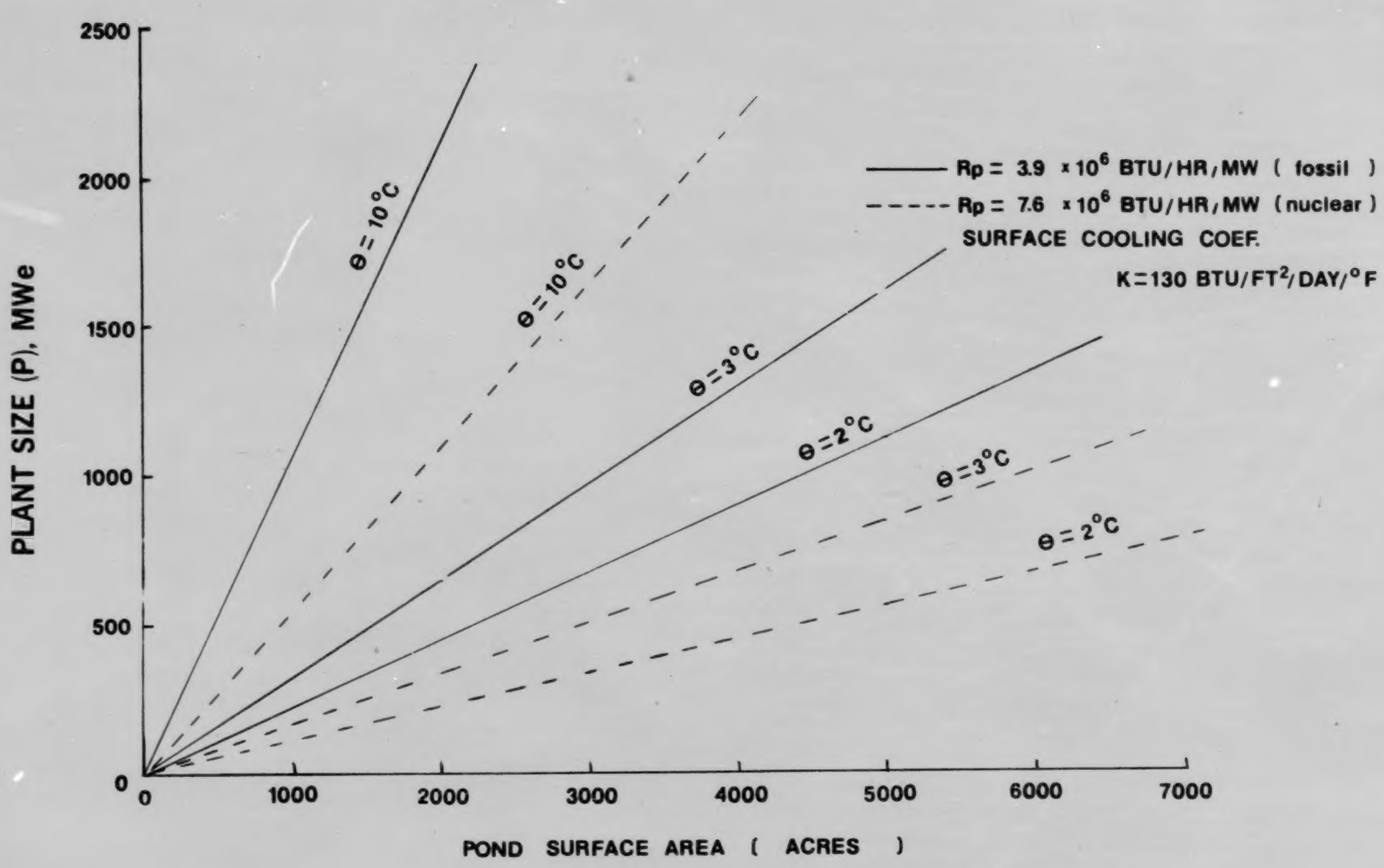


FIGURE 47. AVERAGE TEMPERATURE RISE OF RECIRCULATED FULLY-MIXED POND

TABLE 8. PRELIMINARY SCREENING OF THE AREA OF ONCE-THROUGH SHALLOW WATER BODIES REQUIRED TO MAINTAIN A PERCENTAGE OF THE POND AREA BELOW AN EXCESS TEMPERATURE OF 3°C (Plant ΔT = 15°C)

Power Output (MW)	Pond area in acres required such that x% is subject to an excess temperature less than 3°C		
	x: 95%	90%	85%
500 fossil	12900	6450	4300
750 fossil	19350	9675	6450
1000 fossil	25800	12900	8600
500 nuclear	22162	11081	7387
750 nuclear	33242	16621	11081
1000 nuclear	44323	22162	14774

surface is cooled to 4°C and sinks. In this way, extensive areas of the lake bottom could be covered with water at 4°C. If this unnatural phenomenon persisted throughout the winter, then the successful and normal development of fish spawn such as that for whitefish would certainly be endangered.

A second problem arises through the chronic attraction of fish to the warm water area in the region of the outfall. The larger the percentage of the lake area that this heated region occupies, the greater the number of fish species, particularly cold water forms, that are attracted. Fall spawners may, therefore, have a retarded spawning season and spring spawning may be "triggered" earlier than usual because critical minimum water temperatures would be found in the plume area in advance of similar temperatures in other parts of the lake.

Shifting of spawning seasons, plus the direct effect of warm water at higher than 2°C on fish eggs in the winter, may have a significant effect on the indigenous cold water fish populations.

The above-mentioned criteria would be applied only when it is required that the natural status quo of the lake be maintained. If, however, it is determined that a shift in species diversity is acceptable and that the pond may be used, for example, for the culture of warm water fish, then certainly the temperature and area limits mentioned above can be exceeded. New criteria would then be required from the environmental agency, depending on the ecosystem type that is to be created.

The third bio-thermal constraint identified in the preliminary data collection phase may pertain to the maximum mean surface temperature allowable at the lake surface over a twenty-four hour period; this limitation was explained at the beginning of this section. In making the preliminary evaluation of existing shallow water bodies as potential sources of cooling water, all three criteria would be advanced in the preliminary phase and satisfied during the screening process.

6.3.2 Remarks

For shallow water bodies, the literature often recommends a number of rules of thumb for determining the required pond size for cooling. Although rules such as "one acre per megawatt for a fossil fueled plant and 1½-2 acres/MW for a nuclear plant" are possibly useful to a degree, a procedure for screening based on the simple mathematical models illustrated here can lead to a much better appreciation of the variables involved and their interaction. The computational work involved in producing a series of graphical displays for shallow ponds is minimal, and it enables a better comparison of the real problems in preliminary screening on both man-made and natural water bodies, with and without biological restrictions.

6.4 Preliminary Analysis for Stratified Water Bodies

6.4.1 Simplified hydrothermal considerations

Solar radiation causes warming of the surface waters of a deep lake during the spring. Since the warmer surface water is less dense than the cool bottom water, it tends to remain at the surface, insulating the lower layers while continuing to warm. This process continues throughout the summer, with the warm surface layer (epilimnion) gradually increasing in depth, until some time in the fall when it becomes unstable and mixes with the bottom waters (hypolimnion). Not all deep lakes stratify, since the larger the ratio of surface area to depth, the greater the influence of wind-induced mixing.

Another water body in which thermal stratification is observed is the deep reservoir. In this case, stratification is usually caused, or enhanced, by the inflow of waters at a different temperature from that of the reservoir. For instance, the cold water inflow resulting from an upstream reservoir release will tend to sink on entering a downstream reservoir during summer as discussed in Section 4. On the other hand, a warm shallow river flowing into a reservoir may "float" on the surface. Again, the season and exact shape of the reservoir will in part determine the extent of thermal stratification.

The presence of summer stratification and its average duration under natural conditions will normally be determined in the data analysis stage if the deep lake or reservoir is to be used for power plant cooling.

As indicated in Section 4, the stratified lake or reservoir represents a potentially attractive source of cool water during the summer when the hypolimnion waters may typically be 10-25°F cooler than the surface waters. However, in lakes containing important aquatic organisms this cold water layer can be a refuge for these organisms during periods of excessively high surface layer temperatures. For this reason, many generating stations use both a surface intake and outfall. In this case, only the epilimnion waters are heated (as long as the average epilimnion temperature is not more than a few degrees Celsius above natural conditions) and the cold water supply remains essentially undepleted and available to most of the biota.

The alternative intake-outfall configuration is that of a deep water intake and surface outfall. Since this is more thermally efficient, and as many Canadian lakes do not support important aquatic species, it is necessary to examine both surface and deep water intakes in this section.

6.5.2 Surface intake, surface outfall

Estimating the potential generation capacity of a power plant using once-through cooling situated on a stratified water body can be greatly simplified at the screening stage. During summer stratification, the epilimnion may be considered as a separate shallow cooling pond as discussed in Section 3 and 4. As before, the shape of the surface of the lake and the location of the intake and outfall will determine the predominant flow regime, i.e. completely-mixed, plug flow, or "intermediate" and once-through or recirculating. At the screening of alternatives stage, even a lake with a very irregular surface boundary may fall into the "intermediate" category. Depending on the location of the intake or outfall, it will be possible to visualize the flow regime as "plug flow with sidearms" (as described in Section 3) or as some combination of plug flow and completely-mixed elements. In such situations, it will be possible to analyse a specific lake using a combination of the methodologies outlined in the previous section.

When no distinct stratification is observed, the shallow lake methodology (described in Section 6.2) can again be adopted at the screening stage, but in this case the available cooling will be underestimated to some extent due to additional cooling as a result of mixing of the surface waters with bottom waters. Consequently, the resulting estimate of potential power plant capacity should be regarded as being fairly conservative.

6.4.3 Deep water intake, surface outfall - no inflow

This intake/outfall configuration in a stratified lake or reservoir represents the most complex hydrothermal condition discussed in this report. Consequently, a number of important simplifying assumptions are required to present an analysis for screening thermal power plant locations on these water bodies. The relationships developed in this section and the considerations examined in Section 4 are an attempt to include the predominant hydrothermal data in initial screening studies.

For a deep stratified lake or reservoir with a negligible inflow (approximately equal to the natural evaporative losses during periods of stratification) the following simplifying assumptions are required:

i) Thermal stratification is present for a four-month summer period.

ii) The average depth of the lake is in excess of 50 feet.

iii) The temperature rise across the condensers will be similar to that from the surface to the bottom of the lake. This implies no net warming of the surface layer (epilimnion) due to the cooling water discharge. However, the analogy will also be applicable if the epilimnion is warmed by only a few degrees Celsius.

iv) The average hypolimnion volume, V_h, is known as a percentage of the total volume, V_t, or these data can be estimated during the preliminary data collection phase.

In the situation where no important biota are present in the lake, the total volume of cool water available for once-through cooling over a period of stratification is V_h, the average volume of the hypolimnion. Therefore, the maximum cooling water pumping rate, Q_p. can be estimated by:

$$Q_p = \frac{\text{Total available cold water volume}}{\text{Duration of stratification}}$$

$$Q_p = \frac{V_h\ (\text{ft}^3)}{120\ (\text{day}) \times 86400\ (\text{sec/day})} \tag{7}$$

In circumstances in which a certain minimum volume of cold water must be maintained to protect the biota, this relationship will be modified such that some proportion, x, of the cold water volume is retained.

i.e. available cooling water = $V_h\ (1 - x)$

The pumping rate determined from Equation (7) can be related to a generation capacity if the condenser temperature rise ΔT is known. In this simplified case, ΔT is assumed to be the average temperature difference between the top and bottom of the lake and the equivalent power is given by:

$$\text{Power} = \frac{\Delta T \times \rho C_p\ Q_p}{R_p} \tag{8}$$

where all variables are as defined in previous sections. In typical units, Equation (8) is written as:

$$\text{Power (MW)} = \frac{\Delta T(^{o}F) \times \rho\ (lb/ft^{3}) \times C_{p}\ (Btu/lb/^{o}F) \times Q_{p}\ (ft^{3}/hr)}{R_{p}\ (Btu/hr/MW)}$$

Figure 48 illustrates the relationship between lake volume, volume of hypolimnion (which will depend on the shape and dimensions of the lake) and power plant capacity. This figure is based on a simplified version of the methodology which was outlined in Section 4 and used to construct Figure 23b. The main simplification is the elimination of the variation of the temperature difference between the surface and the intake with increasing intake depth, and its substitution with an assumed constant ΔT. The condenser temperature rise, and also the temperature difference across the lake, is assumed to be about $15^{o}F$ (for other values a new graph can be constructed). No biological constraints relating to the conservation of the hypolimnion have been assumed in Figure 48. In contrast, Figure 49 indicates the reduced capacity available if a limit of 50% is placed on hypolimnion withdrawal. For instance, the maximum fossil fuel generation capacity available on a deep lake having a volume of 4×10^{5} acre-feet and a ratio of hypolimnion volume to total volume of 50% is about 720 MW with no biological constraint, but only 360 MW when the above constraint (50% depletion) is applied.

6.4.4 Deep water intake, surface outflow-inflow

In the present simplified analysis, the inflow to the stratified lake or reservoir is regarded as being either "warm" or "cool". A warm inflow is assumed to enter and leave the water body via the epilimnion, at the same temperature as the epilimnion. In this case, the volume of the hypolimnion is not affected by the inflow and the analysis outlined in the previous section will again be applicable.

Conversely, a cool inflow is assumed to enter the hypolimnion at the average hypolimnion temperature and consequently this inflow will represent a potential additional cooling water supply. The average cool water inflow over the summer will be ascertained in the data collection phase and the additional (above the "no-inflow" capacity) power capacity

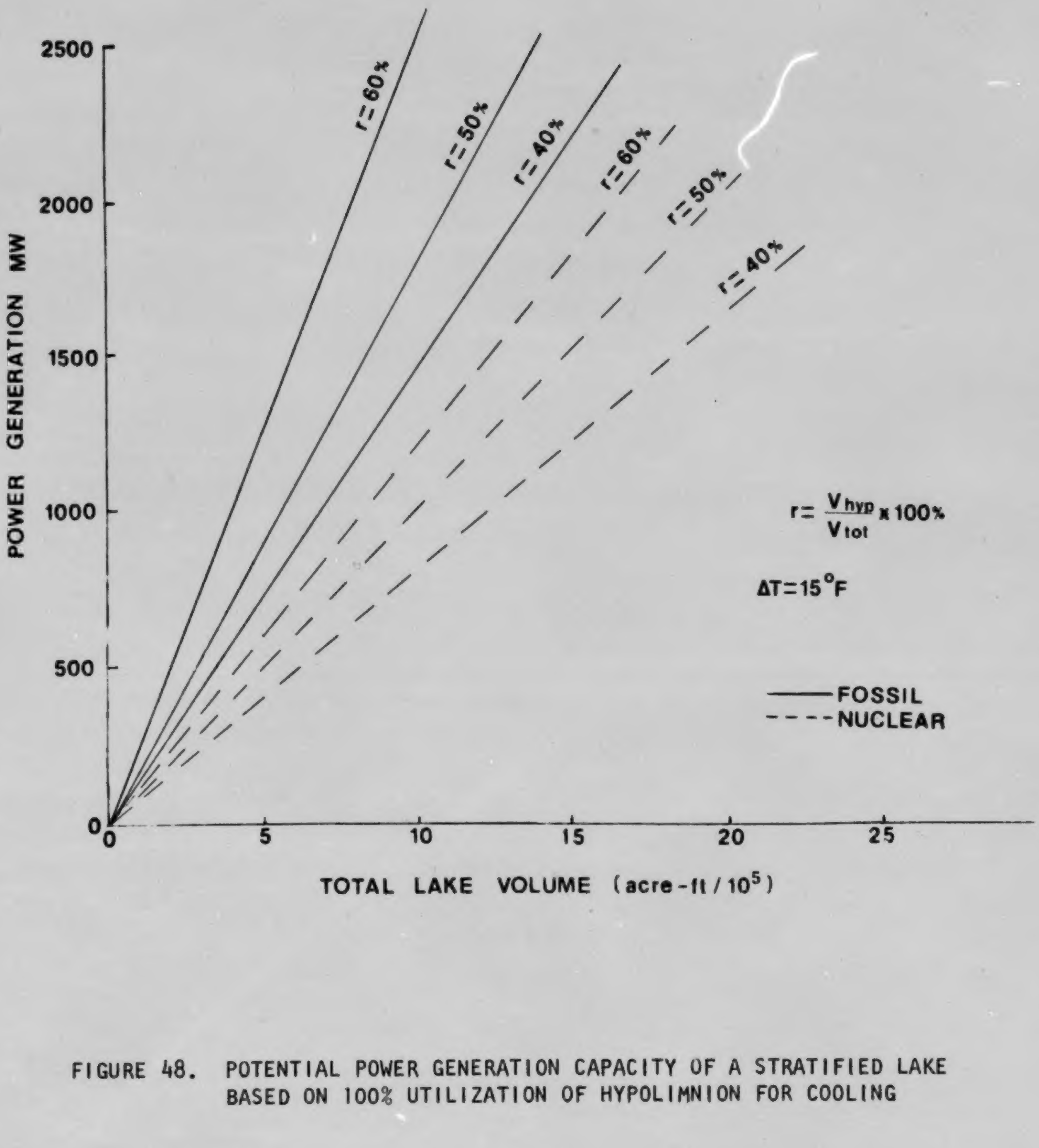


FIGURE 48. POTENTIAL POWER GENERATION CAPACITY OF A STRATIFIED LAKE BASED ON 100% UTILIZATION OF HYPOLIMNION FOR COOLING

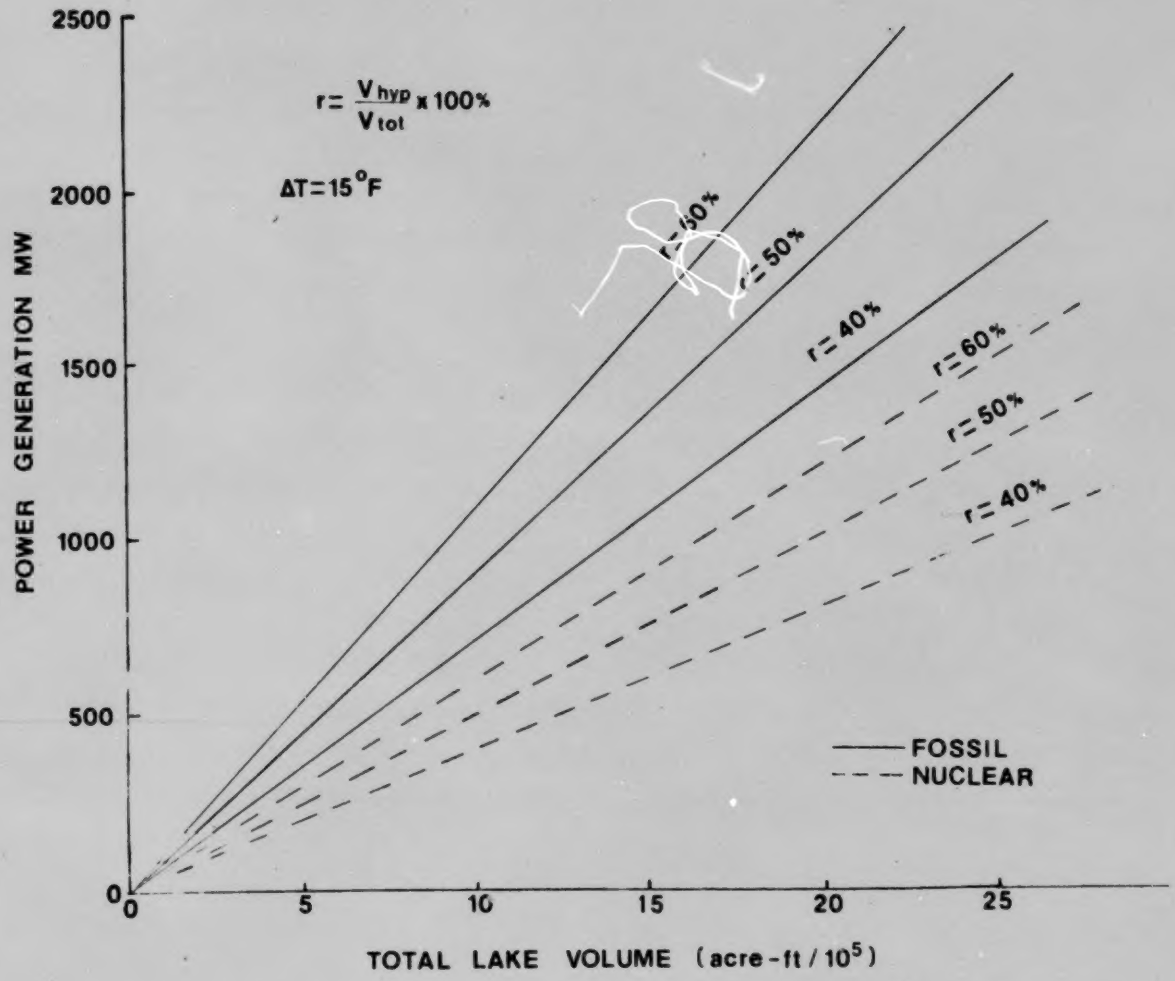


FIGURE 49. POTENTIAL POWER GENERATION CAPACITY OF A STRATIFIED LAKE BASED ON 50% UTILIZATION OF HYPOLIMNION FOR COOLING

can be determined directly from Figure 50. Alternatively, the total generating capacity can be calculated from Equations (7) and (8) when the cool water supply is specified as follows:

$$\text{(Available cooling water)} = \text{(Volume of hypolimnion)} + \text{(Total cool inflow over period of stratification)}$$

Again, this potential total cooling water supply may be limited by some constraint on hypolimnion depletion. However, the method of analysis is similar in either case. For instance, if there is an average cool water inflow of 300 cfs to the lake of 4×10^5 acre-feet volume discussed in the previous section, the potential fossil fuel generating capacity is increased by 260 MW from 720 MW to 980 MW.

6.4.5 Epilimnion heat dissipation

Additional generating capacity may be provided in any of the above situations if it is permissible to raise the epilimnion temperature. This is because excess heat may then be dissipated at the surface (as in the cooling pond situation), rather than stored within the lake. For a lake reservoir of a known surface area, this extra capacity may be calculated in exactly the same manner as outlined for shallow lakes and ponds in the previous section. As with the cooling pond, an idealized (epilimnion) flow regime must be selected, i.e. completely mixed, plug flow or intermediate. For example, if the lake (of volume equal to 4×10^5 acre-feet described in the previous examples) has a surface area of 2000 acres, an additional fossil fuel capacity of 450 MW would be available, for a mean excess epilimnion temperature of $2^\circ C$, based on the "completely-mixed, recirculated" analogy (see Figure 47). The total potential capacity of a power plant using once-through cooling is related to the potential cooling capacity as shown in the diagram on page 204.

6.5 Preliminary Analysis for Rivers

6.5.1 Simplified hydrothermal considerations

As discussed in Section 5, river flows are subject to great variability both on a daily and seasonal basis. In addition, minimum flows will vary from year to year. If a river is to be considered as a

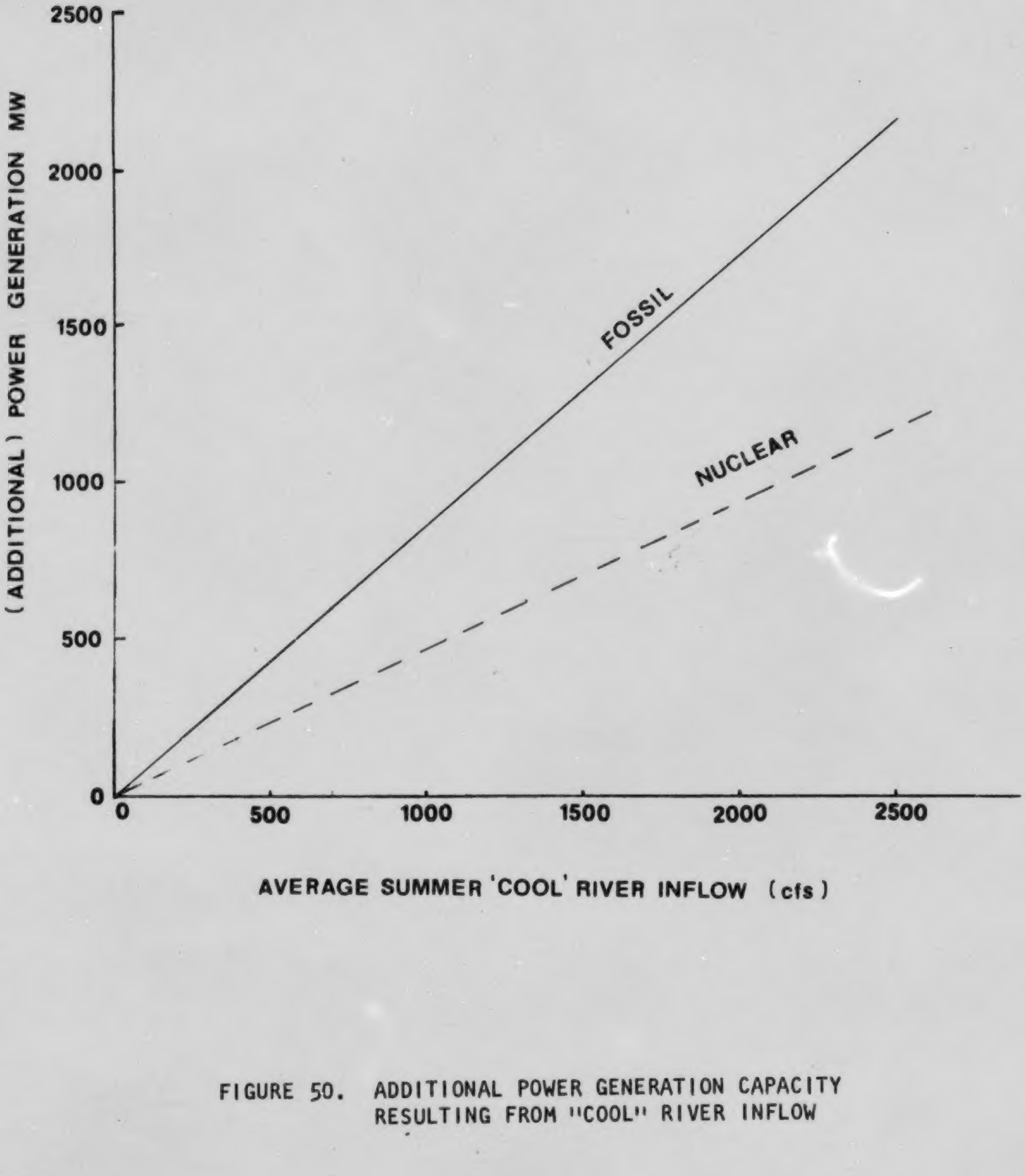
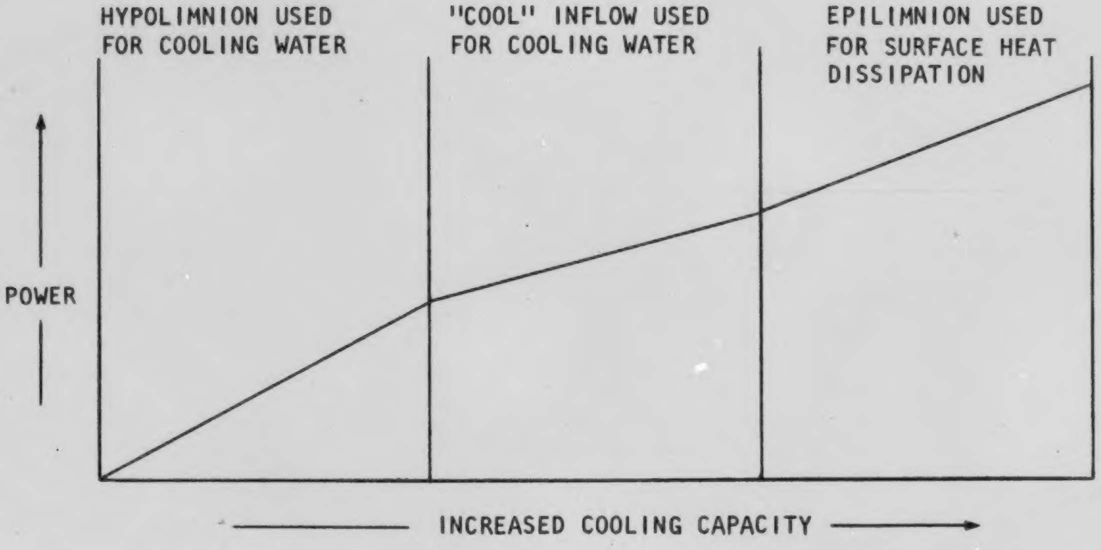


FIGURE 50. ADDITIONAL POWER GENERATION CAPACITY RESULTING FROM "COOL" RIVER INFLOW



source of once-through cooling water, data on the magnitude and duration of low river flows must be assessed at the data collection phase. The source of these data will most probably be historical gauging station records in the case of major rivers. However, for ungauged smaller rivers, it may be necessary to synthesize flows based on meteorological data, such as precipitation, temperature and evapotranspiration, and physical characteristics of the drainage basin.

6.5.2 Operational constraints

The plant capacity and heat rejection rate will have been established in the data collection phase and it is assumed that the maximum acceptable cooling water temperature in the condenser can be estimated. Based on these data, the minimum cooling flow, Q_{min}, required to maintain maximum generation capacity can be computed as follows:

$$Q_{min} = \frac{RpGe}{\rho C_p \Delta T} \text{ (ft}^3\text{/hr)} \qquad (9)$$

where: Rp = heat rejection rate per unit of electrical production (Btu/hr/MW),

Ge = maximum output (MW),

ρ = density of water (lb/ft^3),

ΔT = temperature rise across condenser (^{o}F),

C_p = specific heat of water (Btu/lb/^{o}F).

The condenser temperature rise, ΔT, can be written:

$$\Delta T = (T_o - T_i)$$

where T_o is the specified maximum cooling water temperature and T_i is the intake (or upstream) temperature. The latter will vary throughout the year and may normally be approximated by the equilibrium temperature (discussed in Section 2) when this is above freezing. Consequently, due to the seasonal variation in the maximum potential condenser ΔT, the potential minimum cooling flow requirements will also vary seasonally (See Figure 51).

The choice of a minimum flow criterion (e.g. 7 day - 10 year, 7 day - 2 year, lowest mean daily, etc.) will be determined by the availability of backup production at other plants, or supplemental cooling facilities. The value of T_i (upstream river temperature) should obviously correspond to the average river temperature during the low flow period.

6.5.3 Water quality constraints

As in the previous sections, biological constraints can be translated into simple river temperature constraints. These temperature restrictions will reflect two principal concerns:

i) avoidance of downstream temperatures that would be lethal to aquatic organisms, or that would disrupt normal life cycles; and,

ii) avoidance of depletion of downstream dissolved oxygen to lethally low concentrations.

In the immediate vicinity of the outfall, and in the mixing zone (the region between the outfall and the point downstream where the temperature over a cross-section becomes uniform), the former restriction is usually more limiting. This is because the turbulence induced by the discharge tends to enhance atmospheric reaeration in the vicinity of the outfall. Initially, then, the effect of the cooling water discharge can

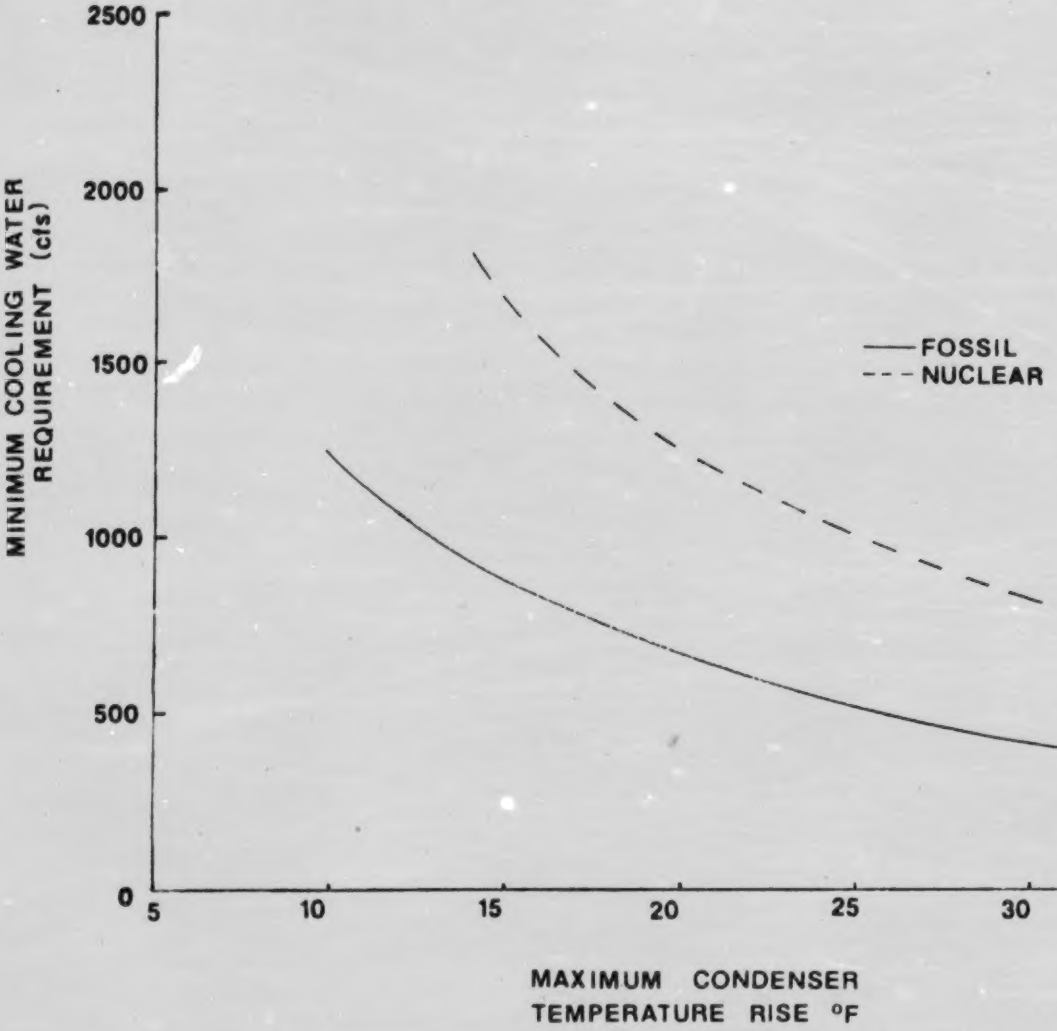


FIGURE 51. MINIMUM COOLING WATER REQUIREMENT (cfs) FOR A 750 MW PLANT WITH ONCE-THROUGH COOLING

be related to the fully-mixed downstream river temperature. When all the river flow is required for cooling, Θ will equal ΔT in Equation (9). The fully-mixed temperature rise, Θ, may be computed from:

$$\Theta = \frac{R_p Ge}{\rho C_p Q_r} \qquad (10)$$

where Q_r is the combined downstream river and cooling water flow. (Note that this is the same equation as (9) but in this case the river flows in excess of those required for cooling are included, thus giving the resulting downstream fully-mixed river temperature.) Θ may be determined directly from Figure 52.

If the fully-mixed downstream temperature proves to be acceptable from the biological viewpoint, it may be necessary to investigate the effect of higher than natural temperatures further downstream. Such excess temperatures may, although being sublethal when considered in isolation, act to deplete dissolved oxygen, thereby creating lethal conditions. For instance, the capacity of water to dissolve gaseous oxygen is reduced with increasing temperature (Figure 53). In addition, higher temperatures accelerate natural instream de-oxygenation rates (k_1, Figure 54). The re-oxygenation rate, k_2, also increases with temperature, but not to the same extent as k_1 (Krenkel and Parker, 1969). Consequently, in many cases the addition of heat to a river can be regarded as the addition of an oxygen consuming waste. In situations where the river-dissolved oxygen is presently low due to municipal or industrial waste discharges, the addition of heat may cause fish kills due to dissolved oxygen depletion, even at "sub-lethal" temperatures.

For an initial assessment of the dissolved oxygen problem, the simple Streeter-Phelps approach (1925) can be adopted:

$$D_t = \frac{k_1 L_o}{k_2 - k_1}\left[e^{-k_1 t} - e^{-k_2 t}\right] + D_o E^{-k_2 t} \qquad (11)$$

where: D_t = concentration of dissolved oxygen below saturation level (Figure 53) at time t (mg/l),

D_o = oxygen deficit at t = 0,

t = travel time (days) = (distance/velocity),

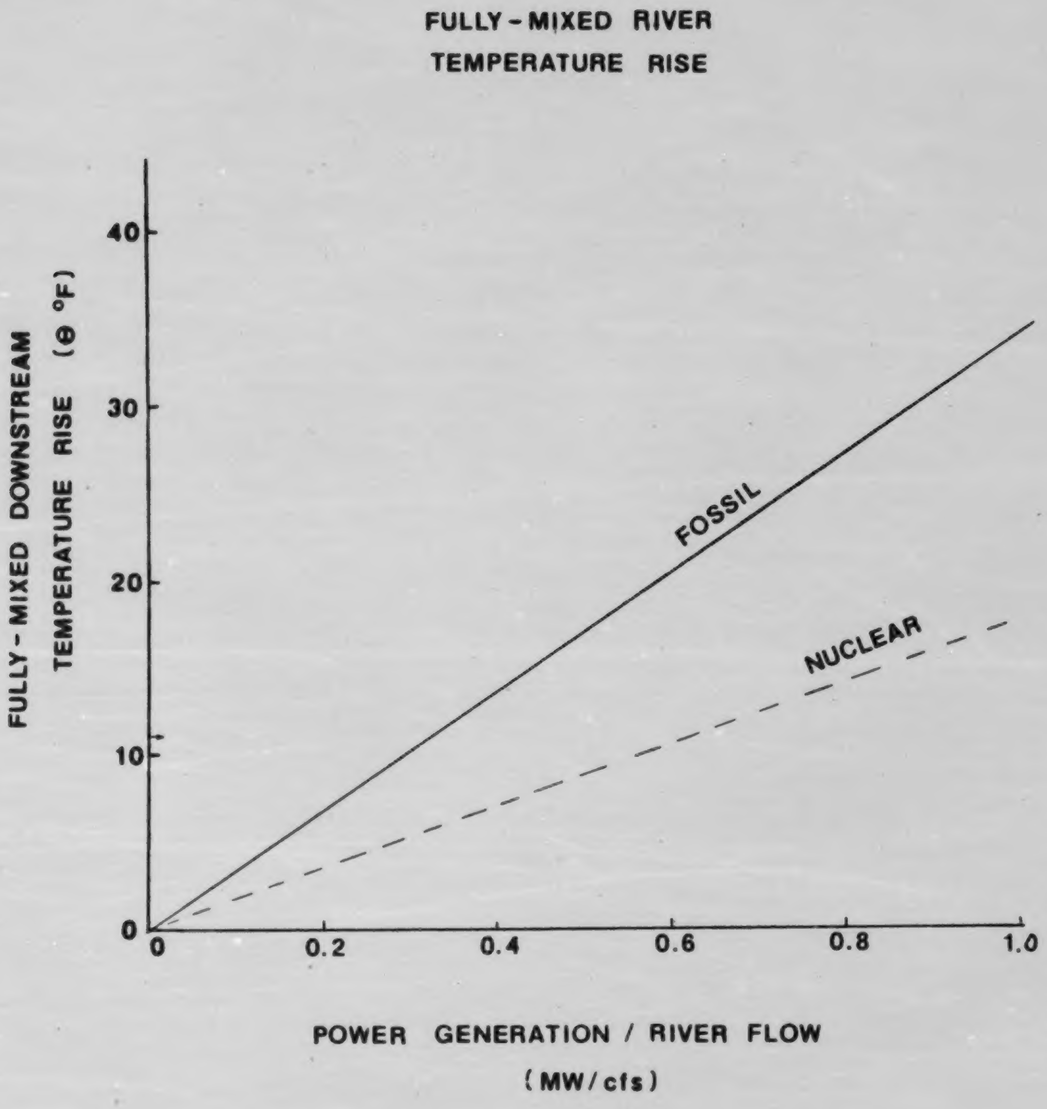


FIGURE 52. FULLY-MIXED DOWNSTREAM TEMPERATURE RISE IN A RIVER

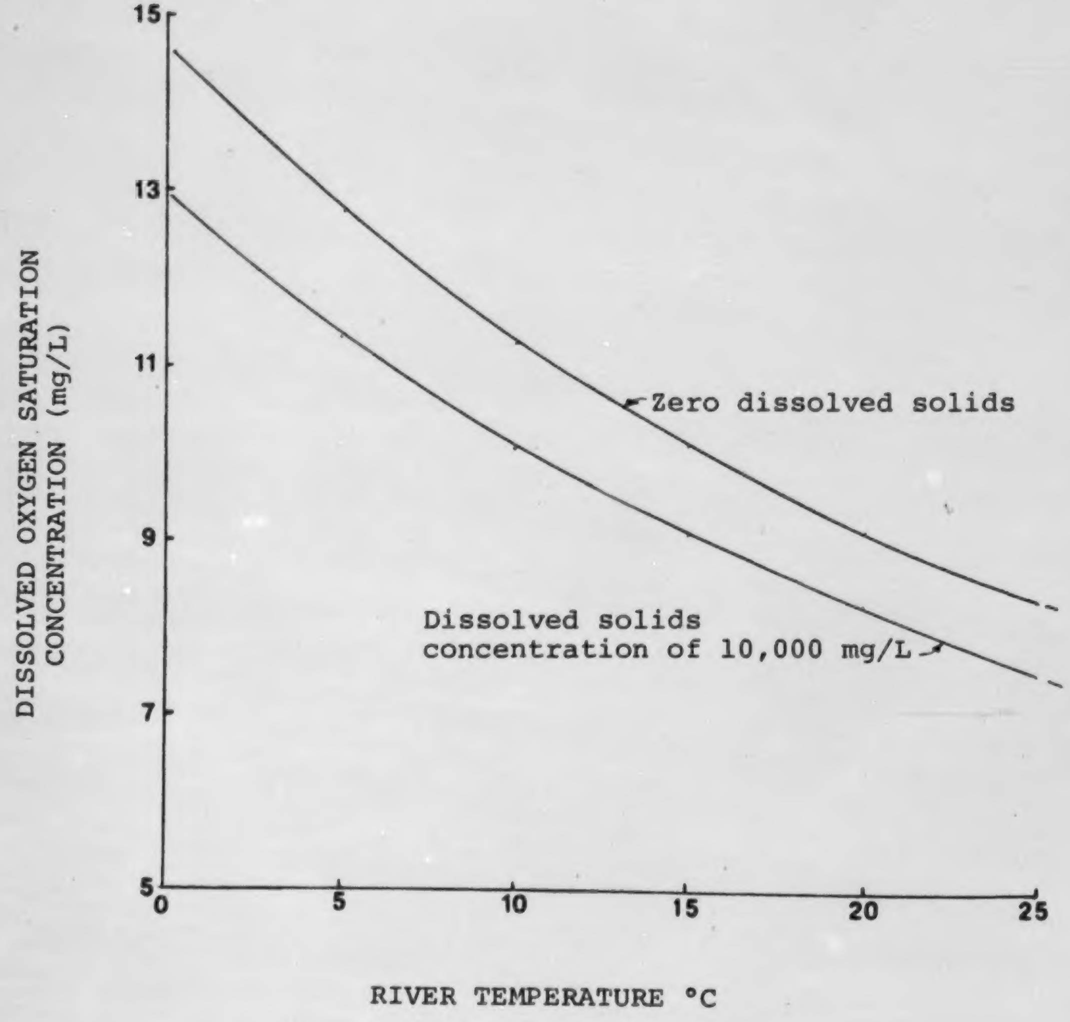


FIGURE 53. DECREASE IN DISSOLVED OXYGEN CAPACITY OF A STREAM WITH INCREASING TEMPERATURE

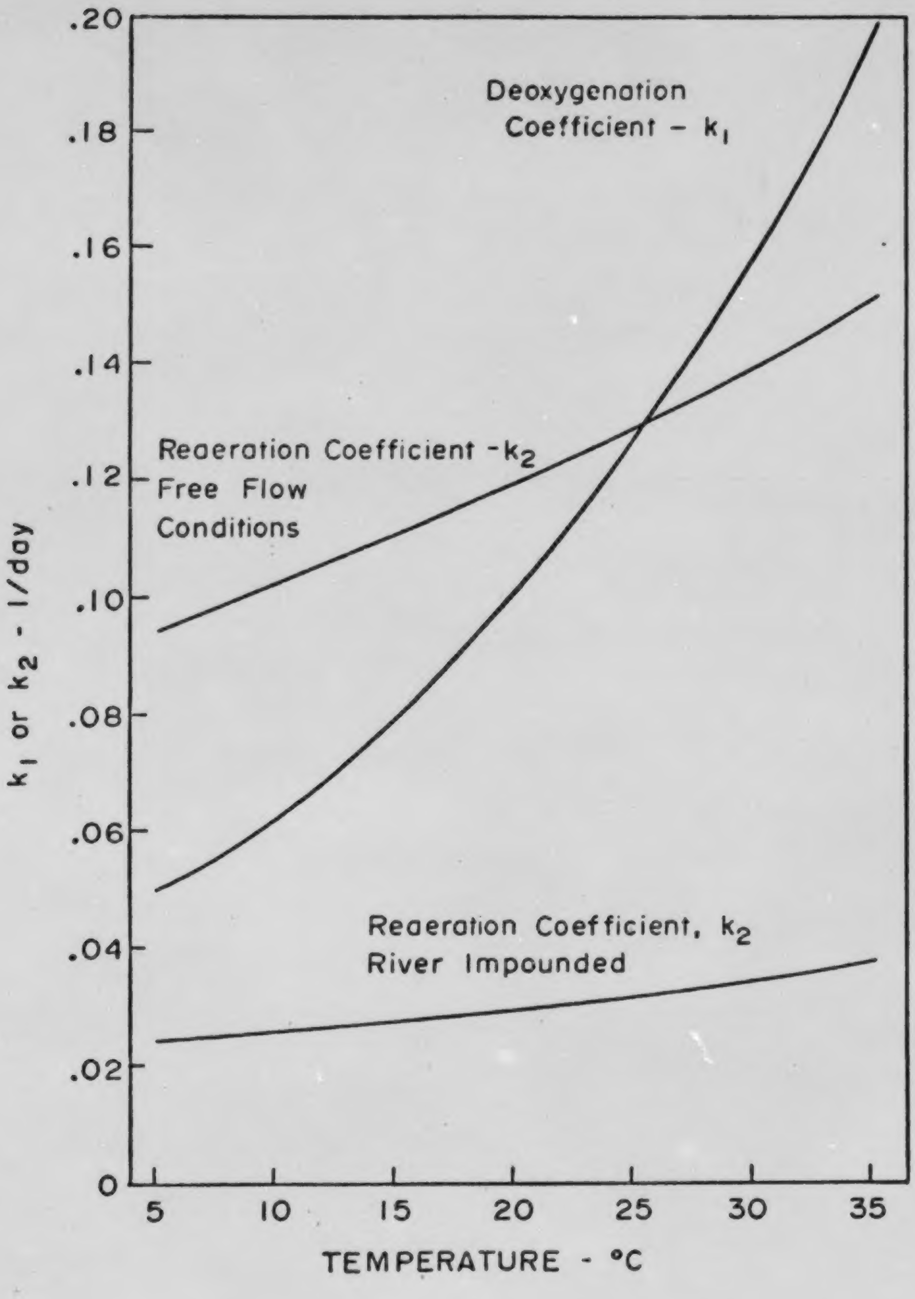


FIGURE 54. VARIATION OF DEOXYGENATION AND REAERATION COEFFICIENTS WITH TEMPERATURE

L_o = initial concentration of an oxygen-demanding waste in slug of water moving downstream with the average velocity (mg/l).

Using Equation (11), the effect of increased water temperatures on dissolved oxygen in a river receiving a known waste load can be approximately evaluated. This analysis would simply involve the comparison of D_t at existing and temperature-increased deoxygenation and reoxygenation rates (Figure 54) for various times, t.

6.5.4 Estimation of length of mixing zone

The length of the mixing zone can be estimated initially by assuming a long straight river channel and using the dimensionless distance coordinate, x*, (See Figure 55) proposed by Edinger et al (1974).

It is evident from Figure 55 that when fully-mixed conditions are established (i.e. there is no temperature gradient across the river), the dimensionless distance, x*, is approximately equal to 0.5. Therefore, the distance to this point may be estimated from:

$$x = \frac{0.5\, ub^2}{D_y} \qquad (12)$$

where: x = downstream distance,

D_y = lateral dispersion coefficient,

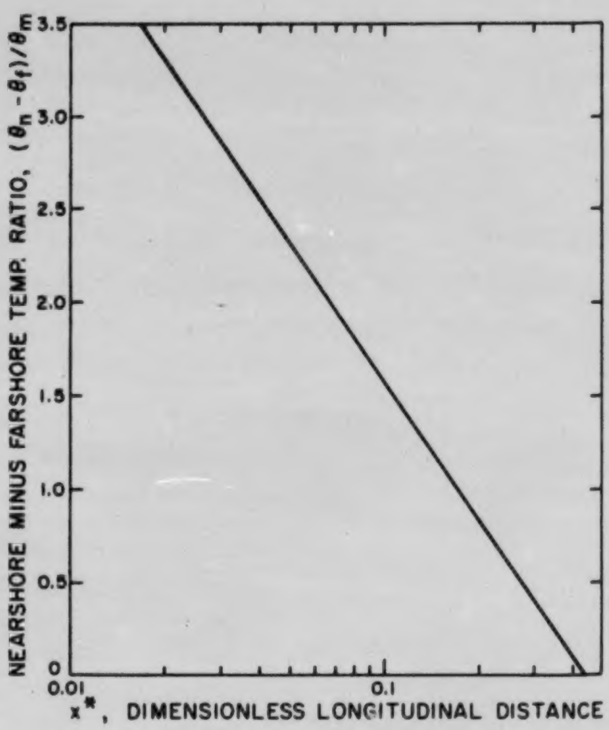
u = average velocity = Q_r/bh,

b = river width,

Q_r = upstream river flow,

h = river depth.

This analysis assumes no surface heat losses in the mixing zone and no initial mixing of the discharge at the outfall. Consequently, there will be a tendency for mixing length calculated by this method to be overestimated. Some typical solutions to Equation (12) are shown in Figure 56 for an assumed lateral dispersion coefficient, D_y, of 10.8 $ft^2 s^{-1}$. The temperature difference between the two shores at distances within the mixing zone can also be estimated from Figure 55, based on an estimate (or measurement) of D_y and the discharge and fully-mixed temperatures.



θ_n = near shore temperature

θ_f = far shore temperature

θ_m = fully-mixed temperature

FIGURE 55. TWO-DIMENSIONAL BOUNDED TEMPERATURE DISTRIBUTION IN TERMS OF NEAR SHORE MINUS FAR SHORE TEMPERATURE VERSUS LONGITUDINAL DISTANCE

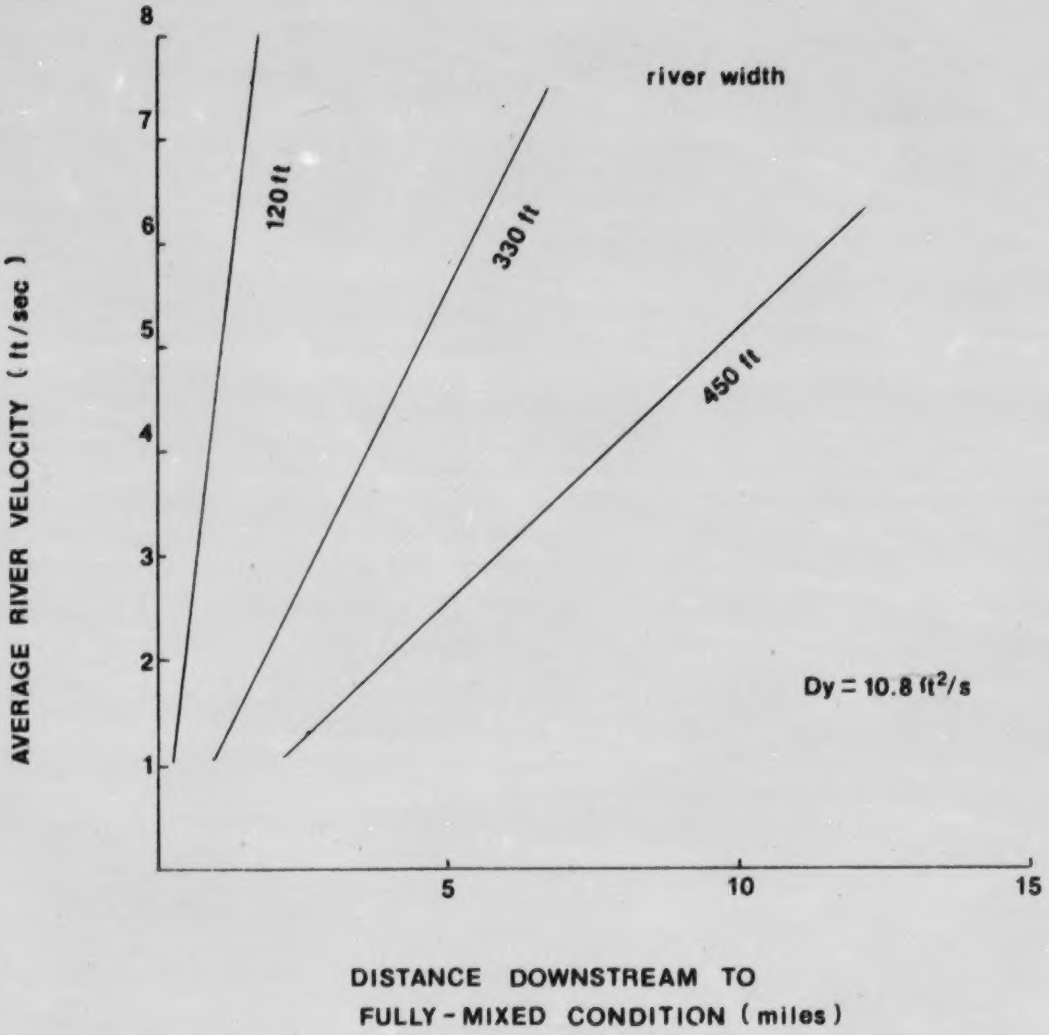


FIGURE 56. ESTIMATION OF LENGTH OF RIVER MIXING ZONE

6.5.5 Estimation of remote downstream temperature

In a major river system it may be necessary to form an initial estimate of the temperature at considerable distances downstream of the cooling water discharge. This might be the case where power plants or other major water users are situated on the downstream reaches of the river. First estimates of downstream temperature can be obtained by visualizing the river as a series of "plug flow" reaches. In effect, this is analogous to treating each reach as a once-through "plug flow" cooling pond as discussed in section 6.2.4. In each reach, a surface heat exchange coefficient must be computed based on average meteorological data. The average tributary inflow to each reach and its temperature must also be estimated.

The initial excess temperature, Θ, is determined from Figure 52 and the "plug flow" equation is used to estimate the reduced excess temperature at the end of the first reach, Θ_1:

$$\Theta_1 = \Theta e^{-KA/\rho C_p Q_r} \qquad (13)$$

Any tributary inflow, Q_t, must then be accounted for before proceeding to the second reach, by assuming complete mixing. The inlet surface temperature then becomes:

$$\Theta_1^* = \frac{Q_r \Theta_1}{Q_r + Q_t} \qquad (14)$$

An additional assumption here is that the tributary inflow is at the equilibrium temperature. Equations (13) and (14) are applied successively for the length of the river or the number of reaches of interest (see Figure 57).

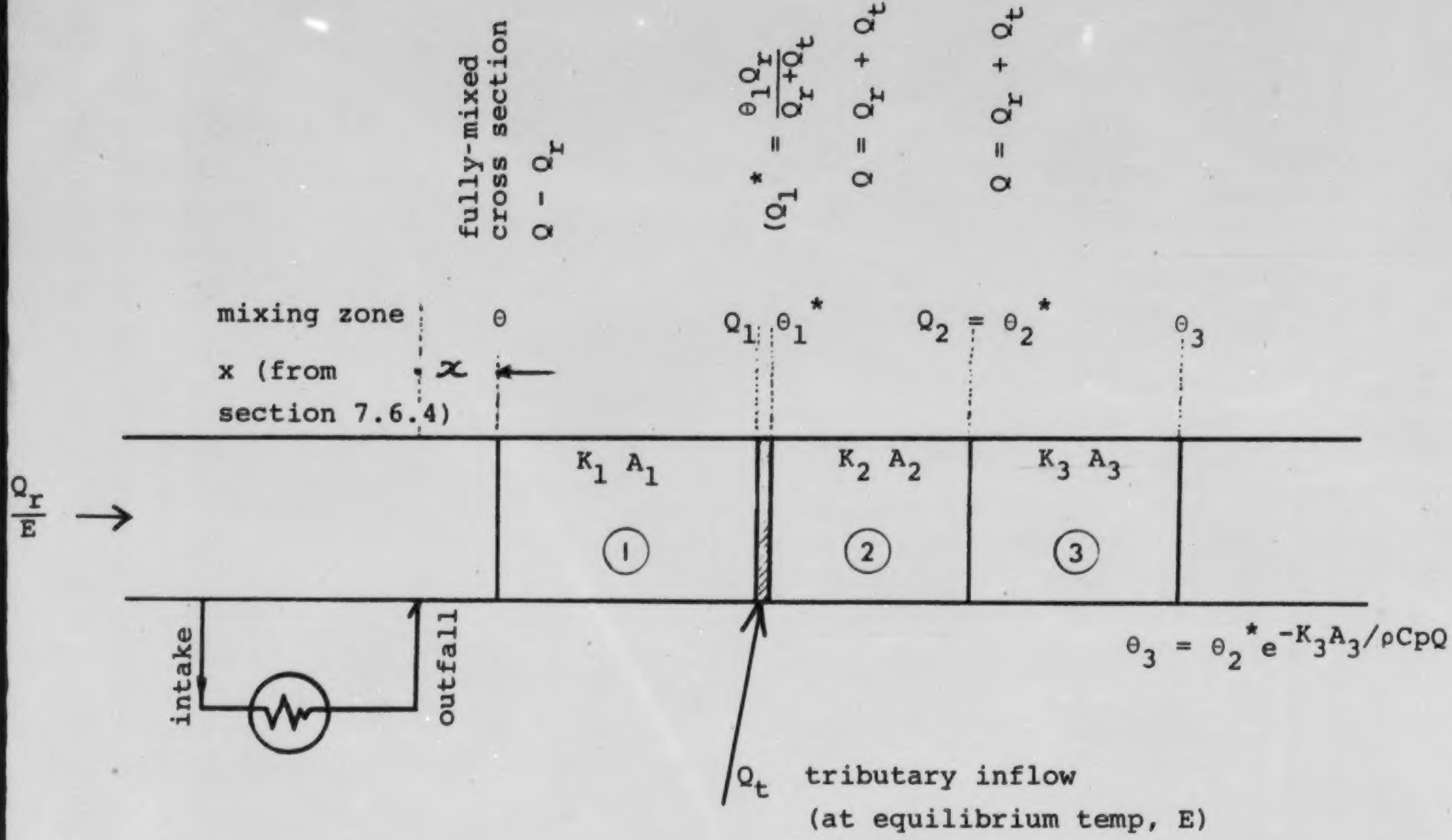


FIGURE 57. REMOTE TEMPERATURE APPROXIMATION SCHEMATIC

7. CONCLUSIONS

1. A small water body has been defined in this study as a body in which the far field hydrothermal effects of a heated discharge can be detected in a major portion or practically all of the water body. Environmental modification due to warming of a small natural water body is consequently not limited to the immediate area of the outfall and, although not necessarily, may be reflected in changes in the ecology of most of the water body. Effectively then, the definition of small water body must link the cooling capability of the entire water body to the cooling requirements of a thermal generating station.

   The possibility of using small man-made or natural water bodies or rivers for condenser cooling is, however, shown to be a viable alternative. In the United States, the Environmental Protection Agency is now considering the use of cooling lakes to be the preferable alternative. In Canada, this option is also particularly important as it may be the only available alternative in provinces having no large water bodies. The use of a small water body may also compare favourably to the use of a large body having sensitive environmental constraints.

2. Small water bodies have been subdivided in this overview into three categories, namely, rivers, non-stratified water bodies, and stratified water bodies. In most instances, however, a particular water body will display features of more than one category, or contain overlapping or obscure segments which may be characteristic of another water body. To aid in heated discharge management, the discussions of each category draw together the characteristic differences in the limnology, morphology, and response of the water body to heated discharge. The focus is then directed to distinguishing differences between each category and to assigning heated discharge management and control alternatives.

   The important characteristics and parameters needed to analyse a small water body considered for cooling use are also defined to ensure that all information is provided for the preliminary siting stage.

3. A screening process was also developed to attack the problem of managing and controlling heated discharge in small water bodies and to obtain an appreciation of the significant role of site-specific variations.

   Both sophisticated and relatively simple mathematical models are available to project the nature of hydrothermal modification in small water bodies. However, considering the number of simple analytical models which give a rapid estimate of the thermal modification, it is recommended that modelling should be a requirement as early as the preliminary siting stage. As was demonstrated in the previous section, the results of these simple models can facilitate environmental, operational and economic comparisons of site alternatives.

   The ease with which simple mathematical modelling can account for site-specific conditions virtually eliminates the necessity to advance broad rules-of-thumb covering extensive geographical areas. This enables the effects of heated discharge to be identified in the preliminary screening of man-made or natural water bodies, with or without biological constraints.

4. Several hydrothermal models were assessed in the discussions of each water body category.

   The HYETA finite difference model was tested and is recommended for general use in predicting detailed thermal regimes in shallow lakes and ponds. The model was compared to other models and proved to be the most attractive in terms of the overall practical implications of its limitations and assumptions.

   The Battelle model, a quasi two-dimensional model, and an improved version of the WRE model are recommended for hydrothermal simulations in stratified lakes and reservoirs that are long and narrow.

   The M.I.T. model is recommended for the case of simple stratified water bodies with regular boundaries.

   The most comprehensive model available for prediction of temperature in rivers is the COLHEAT finite difference model. Although not tested in this study, this model is widely accepted and may be applied in very long and narrow reservoirs.

5. Case studies describing the effects of heated discharge on aquatic biota are also described for each small water body category. Biothermal criteria or objectives to be advanced in the preliminary screening phase can be abstracted from these studies and take the form of: i) an average temperature rise in the entire water body, ii) a distribution of temperature within the water body, or, iii) a maximum allowable surface temperature during a certain period of time. These parameters can be proposed for individual water bodies or for all water bodies in a certain region of the country. A biological monitoring program is also advanced for formulating designs and operational practices for the cooling system of a power plant to be situated on a reservoir.

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The materials presented in this report were obtained through the kind cooperation and assistance of specialists from the Department of the Environment, the Canada Centre for Inland Waters, the Environmental Protection Service in Halifax, the Argonne National Laboratory, Battelle Pacific Northwest Labs, the Johns Hopkins University, the Ralph Parsons Laboratory at M.I.T., the Ann Arbor University, the University of Wisconsin at Milwaukee, the Atomic Energy Commission and Environmental Protection Agency in Washington, and virtually all of the power authorities and organizations in Canada and U.S.A. The selection of materials and presentation of viewpoints was done by the writers, not as a general cross-section but considering mainly Canadian needs and problems. It is felt that subjectivity in comments and, to some extent, arbitrary decisions in the selection from the considerable amount of controversial data, could not be avoided.

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APPENDIX A

A BRIEF REVIEW OF EVAPORATION THEROY

In small water bodies which serve as cooling ponds for thermal discharges, the major component of the cooling process is evaporation. The rate of evaporation increases with the surface temperature, because of an increase in saturation vapour pressure with temperature. For cooling to take place the surface temperature of the cooling pond must exceed the equilibrium temperature. The role of evaporation in the dissipation of heat from cooling ponds was shown in Figure 5 (Edinger et al, 1974).

Energy used by evaporation is a major term in heat budget equations accounting for 40-70% of the heat transfer. Yet it is one of the most difficult to determine. Evaporation from a water surface occurs as a result of both wind driven and free convection. Above a natural water surface, wind driven convection dominates. Above a heated water surface, both processes may be important. The evaporation from a water surface is usually written:

$$E = \rho f\ (W_z)\ (l_s - l_z) \qquad \text{(A.1)}$$

where: E = evaporation expressed in mass flux (mass/area/time),
ρ = density of water,
W_z = wind speed at height z,
$f(W_z)$ = function of wind speed,
l_z = vapour pressure at height A,
l_s = water surface vapour pressure.

For wind-driven convection the wind speed function normally takes the form:

$$f\ (W_z) = (a + b\ W_x) \qquad \text{(A.2)}$$

where a and b are constants which depend mainly on the area considered and its climate. Several researchers have proposed expressions for wind speed functions. Figure A.1 shows some plots of these wind speed functions and Table A.1 shows the corresponding evaporation formula used (M.I.T., 1972).

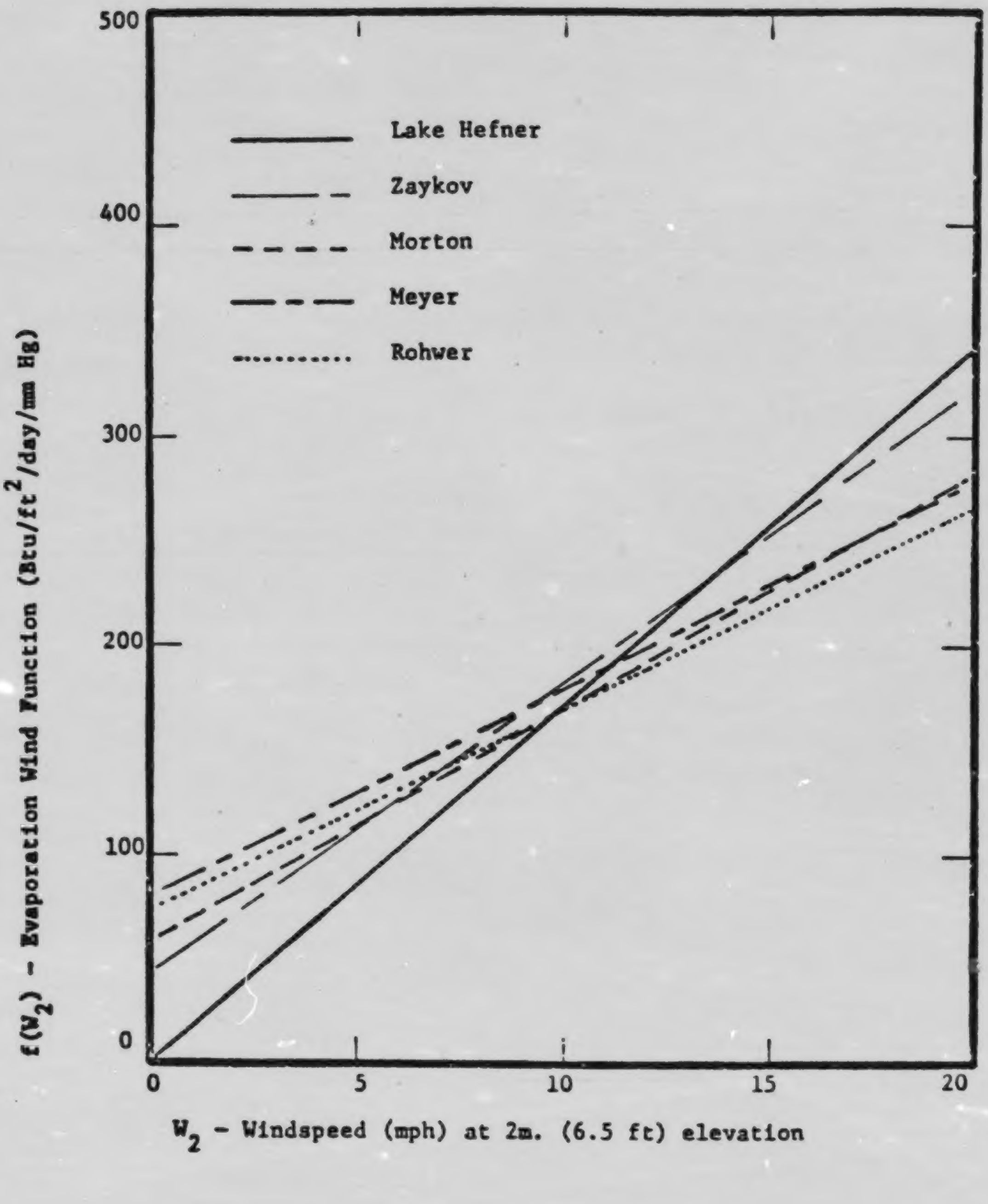

FIGURE A.1. WINDSPEED FUNCTIONS FOR A NATURAL WATER SURFACE

The various evaporation equations are not readily comparable because different heights are stipulated for the wind speed measurements. Furthermore, the empirical constants are calibrated using evaporation data obtained from different types of water bodies. Two lakes of different dimensions, under the same meteorological conditions, will have different evaporation rates. This is because heat advection plays an important role in evaporation near the boundary of the lakes.

The Lake Hefner equation (Marciano and Harbeck, 1952) and the Lake Colorado City equation (Koberg et al, 1959) are based on sufficiently extensive data to yield good results under a wide range of conditions. The Lake Hefner formula can be written as:

$$H_e = 17.2\ W_2\ (e_s - e_2) \qquad \text{Btu/ft}^2 \qquad \text{(A.3)}$$

where W_2 is the wind speed in mph at two metres above the surface, e_s the surface vapour pressure in mm Hg, and e_2 the vapour pressure at two metres above the surface.

Evaporative water losses can be calculated from evaporative heat loss formulas by converting heat transfer to mass transfer using the latent heat of evaporation. The latent heat of evaporation is given as follows:

$$L = 1087 - 0.54\ T_s \qquad \text{(Btu/lb)} \qquad \text{(A.4)}$$

for a given surface temperature T_s ($^\circ$F).

Free convective evaporation takes place only from warm water bodies. Initially, the air in contact with the water surface becomes warmed and saturated; due to buoyancy this air then moves up, allowing more water to evaporate. The analysis of evaporative processes when both forced and free convection are significant is very complicated. Ryan et al (1974) developed a practical approach to the problem of estimating free convective evaporation from cooling ponds. The free convective evaporation loss in heat units is given as:

$$H_e = [\lambda\ (T_{sv} - T_{av})^{1/3}]\ (e_s - e_2) \qquad \text{(A.5)}$$

where: T_{sv} = virtual surface temperature,
T_{av} = virtual air temperature.

TABLE A-1 EVAPORATION FORMULAE FOR LAKES AND RESERVOIRS

Name	Formula in Original Form	Units	Observation Levels	Time Increments	Water Body	Formula at sea-level, Mean. Ht. Spec. units Btu/ft^2/day mph, mm Hg	Remarks
Lake Hefner	$E=6.25\cdot 10^{-4}$ $W_8(e_s-e_8)$	cm/3 hr. knots mb	8m-wind 8m-e_a	3 hrs Day	Lake Hefner Okla. 2587 acres	$12.4W_8(e_s-e_8)$ $17.2W_2(e_s-e_2)$	Good agreement with Lake Mead (138), Lake Eucumbene, Russian Lakes.
Kohler	$E=.00304$ $W_4(e_s-e_2)$	in./day miles/day in. Hg	4m-wind 2m-e_a	Day	Lake Hefner Okla. 2587 acres	$15.9W_4(e_s-e_2)$ $17.5W_2(e_s-e_2)$	Essentially the same as the Lake Hefner Formula.
Zaykov	$E=[.15+.108W_2]$ (e_s-e_2)	mm/day m/s mb	2m-wind 2m-e_a		Ponds and Small Reservoirs	$(43+14W_2)(e_s-e_2)$	Based on Russian experience. Recommended by Shulyakovskiy.
Meyer	$E=10(1+.1W_8)$ (e_s-e_8)	in/month mph in. Hg	25ft-wind 25ft-e_a	Monthly	Small Lakes and Reservoirs	$(73+7.3W_3)(e_s-e_8)$ $(80+10W_2)(e_s-e_2)$	e_a is obtained daily from mean morning and evening measurements of t_a, R_H. Increase constants by 10% if av. of max. and min. used.
Morton	$E=(300+50W)(e_s-e_a)/P$	in/month mph	8m-wind 2m-e_a	Monthly	Class A pan	$(73.5+12.2W_8)(e_s-e_2)$ $(73.5+14.7W_2)(e_s-e_2)$	Data from meteorological stations. Measurement heights assumed.
Rohwer	$E=.771[1.465-.0186B]$ $[.44+.118W]$ $[e_s-e_a]$ where B=atmos. press.	in/day mph in. Hg	0.5-1ft-wind 1 inch-e_a	Daily	Pans 85 ft. diam. tank 1300 acre reservoir	$(67+10W_2)(e_s-e_2)$	Extensive pan measurements using several types of pans. Correlated with tank and reservoir data.

Virtual temperature is given by:

$$T_v^* = T^* / (1 - 0.378 \frac{e}{p})$$

where: e = water vapour pressure at T^*, and

P = atmospheric pressure.

The constant λ has the value 22.4 Btu feet^{-2} day^{-1} mm Hg^{-1} $(^\circ F)^{-1/3}$ or 2.7 $\text{Wm}^{-2}\text{mbar}^{-1}$ $(^\circ C)^{-1/3}$. The complete evaporation formula now takes the form:

$$H_e = [\lambda\ (T_{sv} - T_{ar})^{1/3} + b_o W_2]\ (l_s - l_2) \tag{A.6}$$

in which b and W_2 were defined earlier. Weisman (1975) proposed an aerodynamic approach and suggested an equation of the form:

$$H_e = 1.54 \times 10^{-6}\ U_f\ a\ \left(\frac{X_o}{Z_o}\right)^{-n}\ (e_s - e_a)\ \text{lbm ft}^{-2}\ \text{sec}^{-1} \tag{A.7}$$

where: U_f = friction velocity,

a,n = constants,

Z_o = friction height, and

x_o = wind fetch.

Though Weisman's formula gives results comparable to those from Ryan et al (1974), the method of computation for the latter is more straightforward.

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* Denotes absolute units.

APPENDIX B

EQUILIBRIUM TEMPERATURE (E) AND SURFACE HEAT EXCHANGE COEFFICIENT (K)

The equilibrium temperature, E, is defined as the temperature of the water surface at which the net surface heat exchange is zero (Edinger and Geyer, 1965). This definition of E facilitates the computation of the net rate of surface heat exchange, H_n. The introduction of a coefficient of surface heat transfer, K, (Table 2, Equation (D)) enables the reduction of the seven separate heat exchange terms of Equation (1), Section 2, to a simple equation of the form:

$$H_n = K(T_S - E) \tag{B.1}$$

where T_s is the water surface temperature.

The linearization of Equation (1) in obtaining Equation (D) has been examined in detail by Brady et al (1969) and Edinger et al (1974).

Stefan et al (1972) indicated that the equilibrium temperature and the surface heat exchange coefficient can be approximated by Equations (E) through (G) in Table 2, based on generally available meteorological data.

Over diurnal cycles of heat transfer, it has been found that the short wave radiation term (in Equation (E), Table 2) dominates. On a diurnal basis, the equilibrium temperature can have an amplitude as great as 25°C due to differences in short wave radiation (Edinger et al, 1968). On an annual basis, however, the dew point variation dominates and the equilibrium temperature has an annual amplitude slightly larger than the annual variation in dew point temperature.

For purposes of computation, the excess temperature (θ) of a body of water receiving waste heat can be defined as a perturbation of the ambient water temperature, resulting in a new net rate of surface heat exchange, H_n', at an elevated surface temperature of $(T_s + \theta)$, giving:

$$H_n' = K\ (T_s + \theta - E) \tag{B.2}$$

The increment of surface heat exchange due to a heat source becomes from Equations (D), Table 2, and:

$$H_n' - H_n = K\Theta \qquad (B.3)$$

Consequently, the addition of surface heat loss resulting from the artificial warming of a body of water can be evaluated independently of the equilibrium temperature.

The heat exchange coefficient (K) is an important tool in the study of heat dissipation from small water bodies. As indicated in Equation (F), Table 2, K is a function of the wind velocity and the water surface temperature. Figures B.1 and B.2 indicate values of heat exchange coefficients under natural and heated surface conditions (M.I.T., 1975).

It should be noted that Equation (E) in the Table 2 is a convenient and seldom unsatisfactory approximation of the full equilibium temperature formula:

$$E = (T_d + H_s)/K + (H_a - H_{ar} - H_{sr} - 306 - 4.48\ T_d)/K$$

In this complete formula, which should be used when complete data are available:

T_d = dew point temperature (^oC),
H_s = gross solar radiation (watts/m^2),
H_a = atmospheric radiation (watts/m^2),
H_{ar} = reflected long wave radiation (watts/m^2),
H_{sr} = reflected solar radiation (watts/m^2),
K = surface heat exchange coefficient (watts/m^2/^oC).

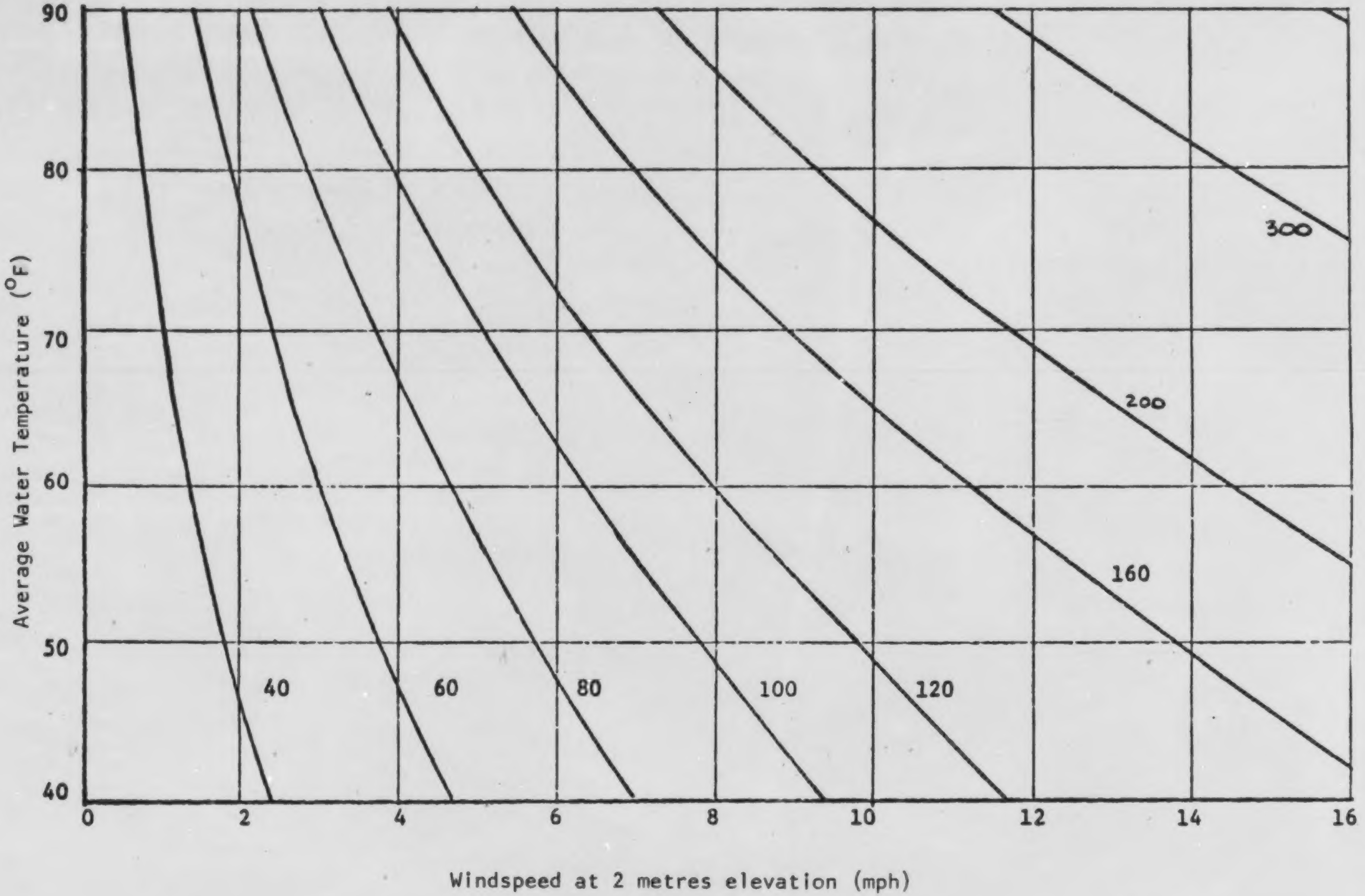

FIGURE B.1. HEAT EXCHANGE COEFFICIENT, K, (Btu/ft^2/day/°F) FOR A NATURAL WATER SURFACE

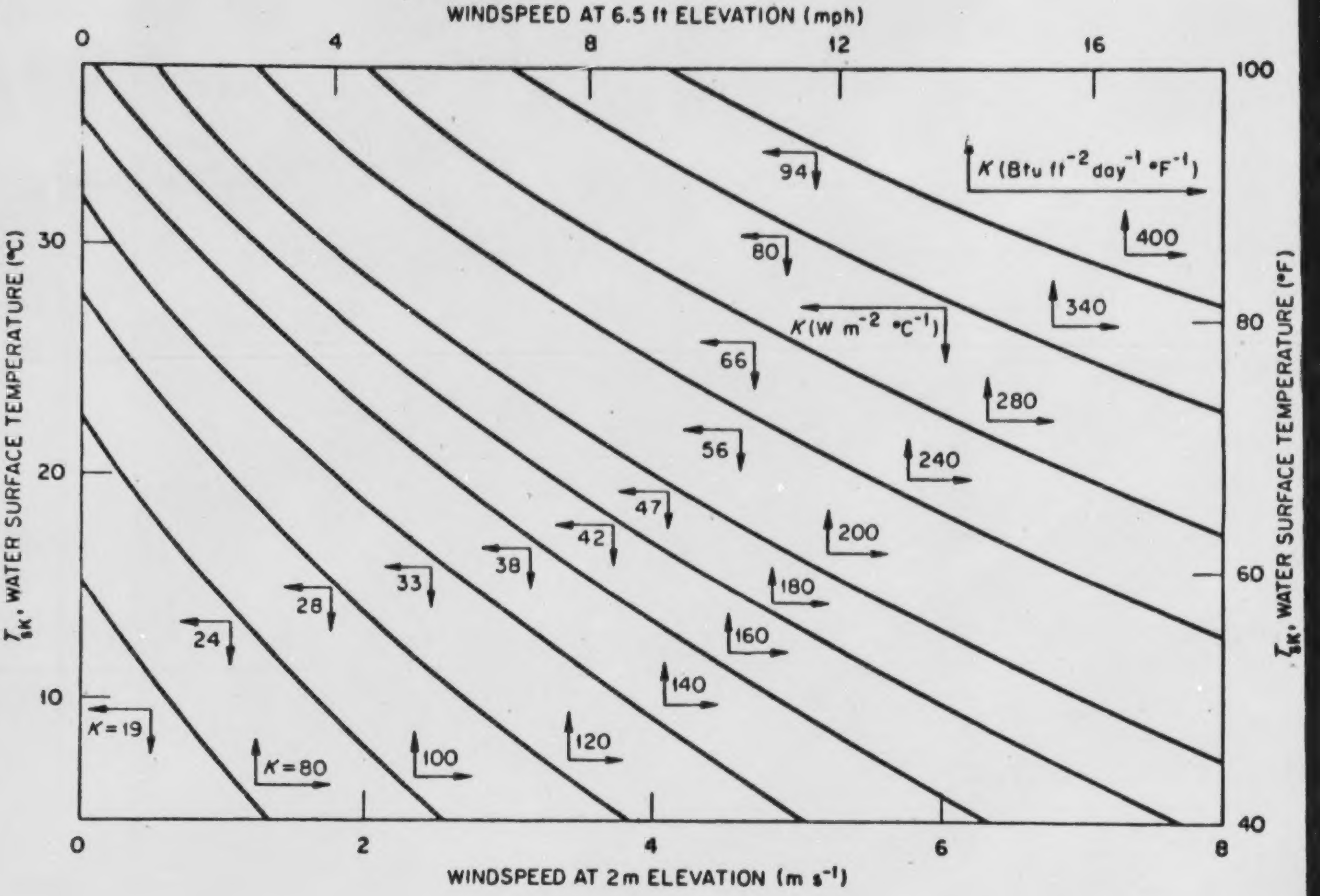

FIGURE B.2. HEAT EXCHANGE COEFFICIENT, K, FOR A HEATED WATER SURFACE $[T_s - T_a = 11^oC\ (20^oF)]$, UNITS FOR K $[W\ m^{-2}\ (^oC)^{-1}]$

APPENDIX C

A TWO-DIMENSIONAL HYDROTHERMAL MODEL FOR SHALLOW WATER BODIES

The HYETA (Hydrodynamic and Excess Temperature Analysis) model is the recommended two-dimensional non-stratified shallow lake and pond model. The HYETA model was originally developed for use in emergency pond analysis by Edinger et al (1972). However, it is directly applicable to the analysis of small shallow water bodies in general. The model uses explicit finite difference techniques to solve the vertically-averaged equations of fluid motion and heat transport.

Its selection was based on the theoretical completeness of the governing equations, flexibility in terms of dealing with a variety of different water body configurations, the availability of the model, and the results of model testing. Some of the model limitations and features of interest with respect to this particular model are as follows:

1. The velocity field is determined from the time varying equations of continuity and momentum. The velocity field used in the temperature solution can be either time varying or essentially steady state.
2. The nonlinear convective acceleration terms are considered negligibly small and are ignored.
3. The effects of wind shear and bottom drag on the velocity field are accounted for.
4. Variable depths throughout the water body are considered.
5. Initial dilution of heat caused by reverse flows (recirculation) can be modelled.
6. Horizontal heat diffusion in both principal directions is included.
7. Steady state meteorological conditions are employed.
8. Evaporative water losses are estimated.

Transient solutions over periods of hours and days are both useful and economical. The spatial detail with which the solution can be determined is limited by the computer hardware available. A computer listing of the model is included elsewhere in this appendix. The spatial resolution which can be dealt with by this version of the model is limited to 14 x 16 horizontal grid points. This can be accommodated on a machine possessing small core memory capacity (32K bytes). Larger grid systems require proportionately larger computer capacities.

C.1 Theoretical Basis

The formulation is based on finite difference representations of the velocity and temperature fields in the two horizontal dimensions. The velocity field is solved by means of explicit integration of the continuity equation and the momentum relations in the horizontal directions over a fixed grid and a series of consecutive time intervals. The temporal and spatial velocity components so generated are then used in the explicit integration of the heat transport equation.

The equations upon which the solution of the hydrodynamics is based are as used by Reid and Bodine (1963) in work involving storm surges in Galveston Bay. They are presented below:

x - momentum:

$$\frac{\partial U}{\partial t} + g\frac{D\,\partial H}{\partial x} = W_x - \frac{f}{D^2}\,U(U^2 + V^2)^{\frac{1}{2}} \qquad \text{(C.1)}$$

y - momentum:

$$\frac{\partial V}{\partial t} + g\frac{D\,\partial H}{\partial y} = W_y - \frac{f}{D^2}\,V(U^2 + V^2)^{\frac{1}{2}} \qquad \text{(C.2)}$$

continuity:

$$\frac{\partial H}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = R \qquad \text{(C.3)}$$

where: U,V = verically integrated horizontal flows/unit width in the X and Y directions ($ft^2\ sec^{-1}$)
H = elevation of water surface (ft),
D = water depth (ft),
f = nondimensional friction factor,
R = net flow addition/surface area (ft · sec^{-1}),
W_x, W_Y = wind shear on water surface,
g = acceleration due to gravity (ft · sec^{-2}).

The momentum relations contain terms depicting instantaneous acceleration, horizontal pressure gradient, surface wind stress and nonlinear frictional momentum dissipation. The nonlinear convective acceleration terms have been eliminated *a priori* on the basis of order of magnitude considerations.

The excess temperature field equation is derived from the relation describing the two-dimensional transport of excess heat through a water body:

$$\frac{D\partial\Theta}{\partial t} + \frac{\partial U\Theta}{\partial x} + \frac{\partial V\Theta}{\partial y} - \frac{D\partial E_x\partial\Theta}{\partial x^2} - \frac{D\partial E_y\partial\Theta}{\partial y^2} + \frac{K\Theta}{\rho C_p} = \frac{HA}{\rho C_p} \qquad \text{(C.4)}$$

where: Θ = temperature excess (^{O}F),
E_x, E_y = turbulent dispersion coefficient (ft^2 sec^{-1}),
K = coefficient of surface heat exchange (Btu ft^{-2}sec^{-1} ^{O}F^{-1}),
HA = net heat input/surface area (Btu ft^{-2} sec^{-1}).

The first term indicates the change in heat storage over time. The second and third deal with advective heat transport; the fourth and fifth terms with turbulent heat fluxes. The sixth term is the net rate of surface heat exchange. The last term indicates external sources-sinks of heat other than surface exchange.

The coefficient of surface heat exchange summarizes the water temperature dependent heat transfer processes of back radiation, evaporation and conduction. It is estimated from known values of water temperature, dew point temperature, and wind speed according to:

$$K = 15.7 + (0.26 + \beta)\ f(w)\ \text{Btu/ft}^2\text{/day/}^{O}\text{F} \qquad \text{(C.5)}$$

$$f(W) = 70 + 0.7\ W^2 \qquad \text{(C.6)}$$

$$\beta = 0.255 - 0.0085\ T_m + 0.000204\ T^2_m \qquad \text{(C.7)}$$

where: $T_m = (T_s + T_d)/2$ (^{O}F),
W = wind speed as measured 18 feet above water (mph),
T_s = water surface temperature (^{O}F),
T_d = dew point temperature (^{O}F),
β = slope of vapour pressure-temperature curve,
$f(w)$ = wind function.

Evaporative water losses are accounted for in the program according to the following relation:

$$L = \beta\, (T_s - T_d)\, f(w)\, /\, \rho H_L \quad (\mathrm{ft} \cdot \mathrm{sec}^{-1}) \tag{C.8}$$

where: L = rate of evaporative water loss ($\mathrm{ft} \cdot \mathrm{sec}^{-1}$),
ρ = density of water ($\mathrm{lb} \cdot \mathrm{ft}^{-3}$),
H_L = latent heat of vaporization ($\mathrm{Btu} \cdot \mathrm{lb}^{-1}$).

C.2 Solution Technique

Equations (C.1) through (C.4) are expressed in finite difference form and integrated over the solution space using an explicit technique. The three unknowns, H, U and V, are solved throughout the grid system and over short time increments using the three equations which govern the hydrodynamics. The heat transport relation is similarly discretized and solved.

The solution generally follows a two-step procedure in which first, the velocity field is established, and second, the temperature field is solved using the velocity field. The HYETA model provides two optional solution procedures. The first method requires that the velocity field be recomputed at each time step prior to the solution of the temperature field. This yields a fully time-varying solution in which both the velocity and temperature fields are assumed transient. The second method allows the velocity field to be calculated until essentially steady state conditions are achieved, after which the velocities are held constant and the heat inputs initiated. Consequently, the transient temperature computations are conducted in the presence of a steady state velocity field. For the case of closed-cycle cooling ponds, the assumption of a steady state flow condition is usually a reasonable one in the short term (hours, days), provided wind stresses do not vary dramatically. By approaching the solution in this latter manner, an appreciable discount in computer costs is realized.

C.3 Stability and Convergence Criteria

The stability of the hydrodynamics solution is ensured by considering the well-known celerity wave criterion, which states that computations must proceed using a time step that is shorter than the time required for the free surface gravity wave to traverse the distance ΔS.

$$\Delta S/\Delta t > (2\ g\ D_{max})^{\frac{1}{2}}$$

The temperature solution is subject to the following stability and convergence criteria:

$$\Delta t/\Delta S < D/8(u)$$

$$\Delta S^2/\Delta T > 8\ (E_x + E_y)$$

$$\Delta t < \rho C_p D/4K$$

These correspond to the realization that the heat flux out of a volume over a time span cannot exceed the amount of heat originally contained in it.

The criterion governing the rate of solution of the velocity field is often much more restrictive than those of the temperature calculations. By de-coupling their solution as outlined in the preceding section, this difference in criteria can be capitalized on, resulting in cost savings.

C.4 The DO - BOD Option

The model has been expanded by James F. MacLaren Limited to accommodate a second major optional analysis: dissolved oxygen - biochemical oxygen demand. Several similarities exist between the DO - BOD and heat computations. Therefore, portions of the computer program are common to both.

The governing hydrodynamic equations and the corresponding stability criterion are identical for both options. The DO and BOD transport equations are interrelated through reaction coefficients. These equations are presented below:

$$\frac{\partial C}{\partial T} + \frac{1}{D}\frac{\partial UC}{\partial x} + \frac{1}{D}\frac{\partial V}{\partial y} - \frac{\partial(E_x \partial C)}{\partial x^2} - \frac{\partial(E_y \partial C)}{\partial y^2} = K_a(C_s - C) - K_d L + C_a \qquad (C.9)$$

$$\frac{\partial L}{\partial T} + \frac{1}{D}\frac{\partial UL}{\partial x} + \frac{1}{D}\frac{\partial VL}{\partial y} - \frac{\partial(E_x \partial L)}{\partial x^2} - \frac{\partial(E_y \partial L)}{\partial y^2} = -K_r L + La \qquad (C.10)$$

where: C = DO concentration (mg/l),
K_a = coefficient of reaeration (l/day),
K_d = coefficient of oxygen utilization (l/day),
C_s = saturated DO concentration (mg/l),
C_a = external DO sources (mg/l/day),
L = BOD concentration (mg/l),
L_a = external BOD sources (mg/l/day),
K_r = coefficient of BOD removal (l/day),

and other variables are as previously defined.

The following stability and convergence criteria apply:

$$\frac{\Delta t}{\Delta s} < \frac{D}{8\,(u)}$$

$$\frac{\Delta S^2}{\Delta t} > 8(E_x + E_y)$$

$$\Delta t < \frac{86400}{4K_a}$$

$$\Delta t < \frac{86400}{4K_r}$$

Using this option, the distribution of DO and BOD throughout a grid system and at consecutive time intervals can be determined. Similarly, by settling all reaction coefficients to "0", the movement of inert pollutants such as suspended solids over space and time can be simulated.

C.5 Model Testing

The validity of the model has been tested in a variety of ways, ranging from comparisons with analytical solutions in the instance of extremely simple regular shaped water bodies, to agreements based on the simulations of both regular and irregular-shaped water bodies supported by recorded field data.

A number of comparisons have been made between the results of the HYETA model and those of steady state analytical models based on the plug flow analogy, for typical applications to essentially one-dimensional cooling ponds. The results of the HYETA model have shown to compare well with the "known" solutions in these simple cases. Figure C.1 demonstrates

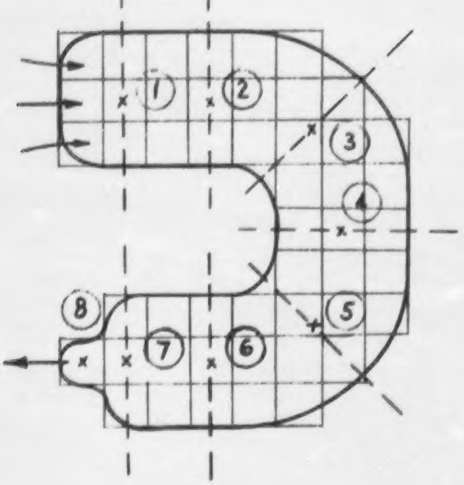

FIGURE C.1(a). LAYOUT FOR COOLING POND TEST CASE

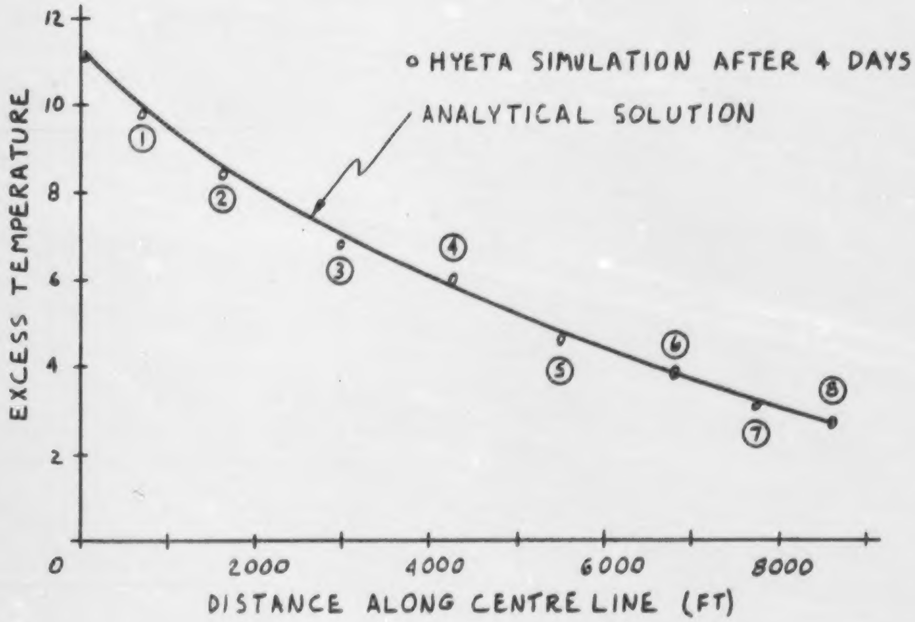

FIGURE C.1(b). LONGITUDINAL TEMPERATURE PROFILE FOR COOLING POND TEST CASE such a comparison in the case of a one-dimensional open cycle pond having a 275 acre surface area, uniform depth of 4 feet and a rate of heat loading of 9×10^9 Btu/hr.

The velocity field simulated by HYETA for a portion of a larger water body bounded on two sides is presented in Figure C.2. In this case the water depth varied considerably with distances from the two shores. The flow essentially follows the bathymetry deflecting towards the east as it approaches the northern boundary. This example demonstrates the ability of the model to produce rational velocity fields in the presence of variable bathymetry. It also illustrates the capability of modelling only a portion of a larger water body.

Figure C.3 presents the velocity field simulated by HYETA for a second situation. Again, only a portion of the water body is modelled with the area of interest bounded on two sides. The water reaches a maximum depth of 18 feet in the north-east corner of the grid. As before, the simulated flow field is seen to behave as expected in the presence of variable bathymetry and solid boundaries. The thermal power plant is located on the south shore and extracts cooling water from one side of a dyke and returns it on the other. The operation of the cooling water pumps is reflected in the velocity field of Figure C.3. This simulation shows that the model is capable of realistically representing flow in the vicinity of an internal dyke or breakwater. Figure C.4 illustrates the distribution of excess heat as given by the HYETA model after ten hours of power plant operation.

The movement of the heat towards the western shore and plant intake is attributed to a combination of ambient velocities and plant-induced flow. It shows that only a small portion of the water surface area is effective in surface cooling and that significant heat recirculation is taking place. This demonstrates the usefulness of two dimensional models in general, and the HYETA model in particular, in determining the portion of the surface area of a pond effective in cooling and the amount of recirculated heat to be expected.

The results from the HYETA model were compared to the results of a temperature monitoring effort undertaken in Horseshoe Lake in July, 1963. The lake is located in Oklahoma near Oklahoma City and provides a

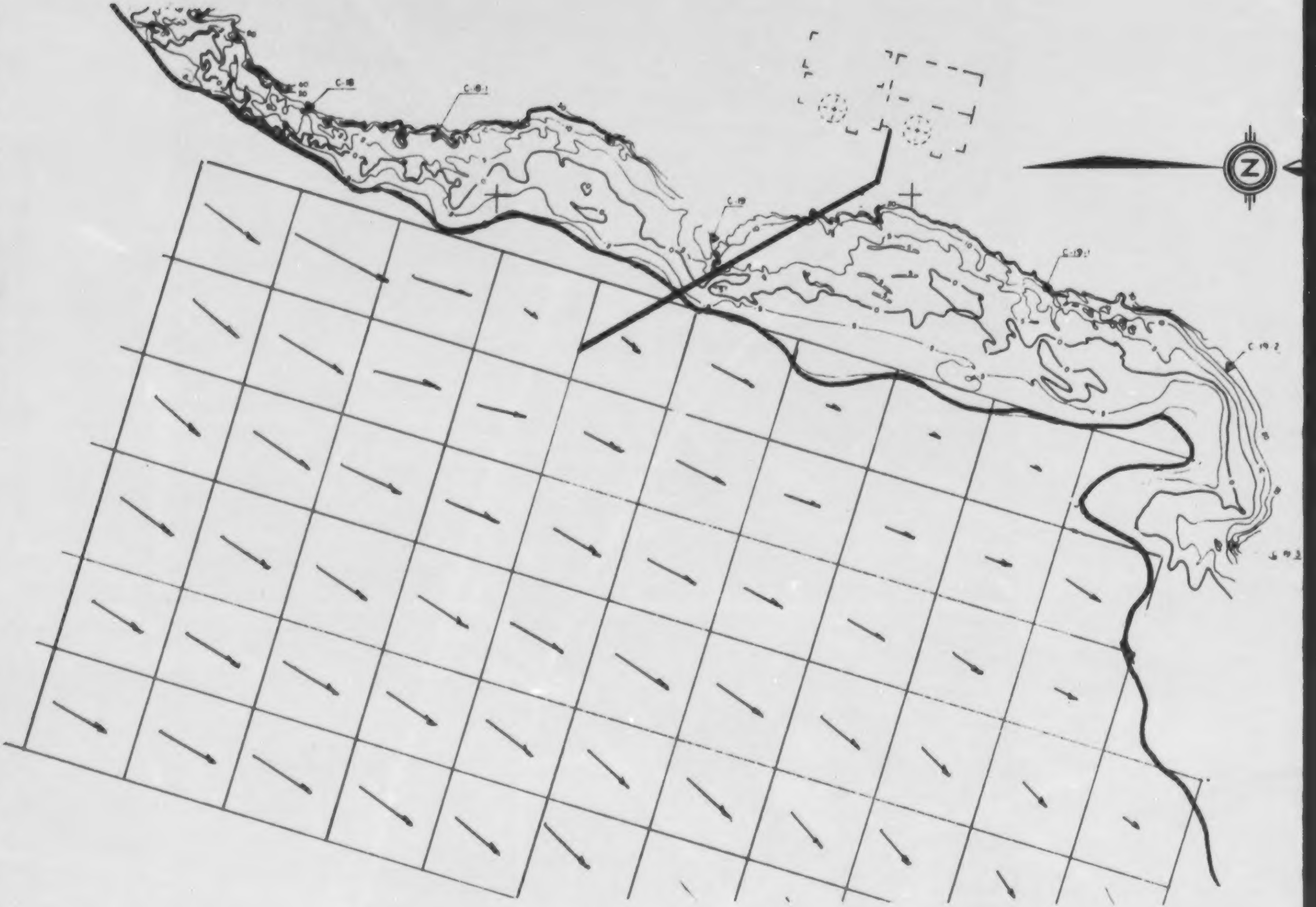

FIGURE C.2. VELOCITY FIELD : VELOCITY SCALE 1 cm = 1 ft/sec, SPATIAL SCALE 1 INCH = 800 ft.

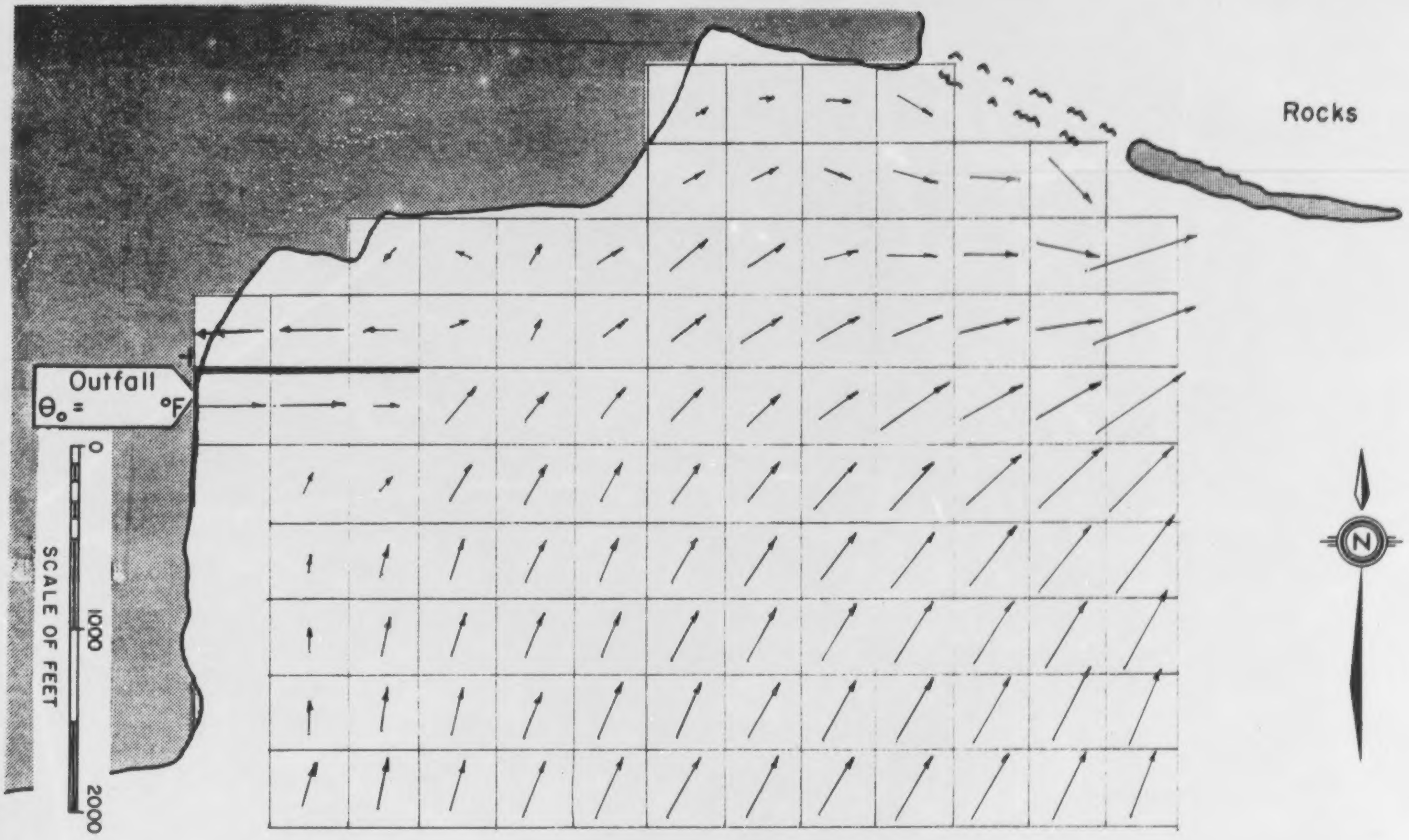

FIGURE C.3. VELOCITY FIELD : VELOCITY SCALE 1 inch = 1 ft/sec

source of cooling water for the Horseshoe Lake Generating Station. The station consists of seven generating units with a total capacity of 470 MW. At the time of the field study, the lake had recently been reshaped and dredged, resulting in a surface area of 280 acres and an average depth of 3.5 feet (see Figure C.5). Temperatures were monitored by means of temperature probes distributed throughout the lake (see Figure C.5a). In addition, temperatures were monitored in a small lake adjacent to Horesehoe Lake to provide estimates of natural water temperatures - Probe 19 (See Figure C.5a). A comparison between results of the HYETA model and the measured data was made for the period from noon to midnight on July 21, 1963. During this span of time, natural water temperature rise and flow rate were found to be a fairly constant, 6.1°C (11°F) and 285,700 US gpm, respectively.

The finite difference grid used by the model is illustrated in Figure C.5(a). The velocity field computed by HYETA and used in the heat transport calculations is presented in Figure C.5(b). Plots of water temperature versus time as given by the HYETA model and as measured at several locations within the pond are shown in Figure C.6. These plots demonstrate a favourable overall agreement between measured data and model results. The average discrepancy between the two results is approximately 1.0°C (1.8°F). The maximum deviation of 2.8°C (5°F) occurs near the intake at the location of Probe 16.

The isotherm pattern as predicted by HYETA at 6:00 p.m. on July 21, 1963 is presented in Figure C.7.

C.6 The Computer Program

The program consists of a main routine and several subroutines. The main program inputs the necessary data, does many of the calculations, and references the subroutines. Subroutines TEMPR and DOBOD perform computations specific to heat and DO-BOD analyses, respectively. The remaining routines serve to output results. A complete source listing is included in this appendix.

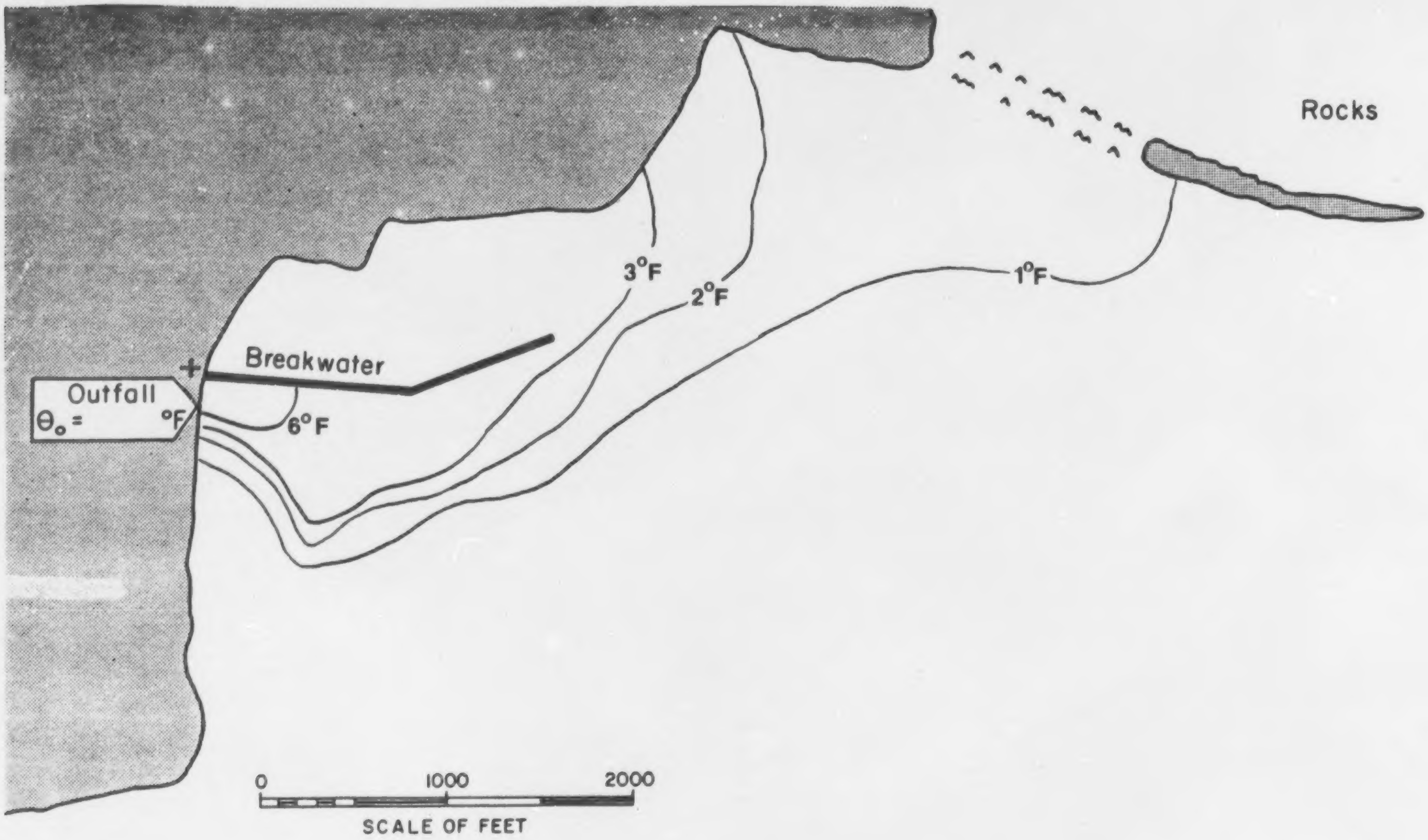

FIGURE C.4. EXCESS TEMPERATURE AFTER TEN HOURS

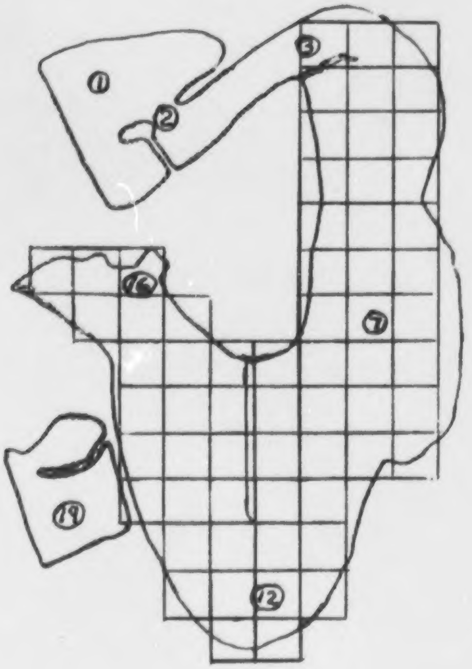

FIGURE C.5(a). LOCATION OF TEMPERATURE PROBES AND FINITE DIFFERENCE GRID SYSTEM

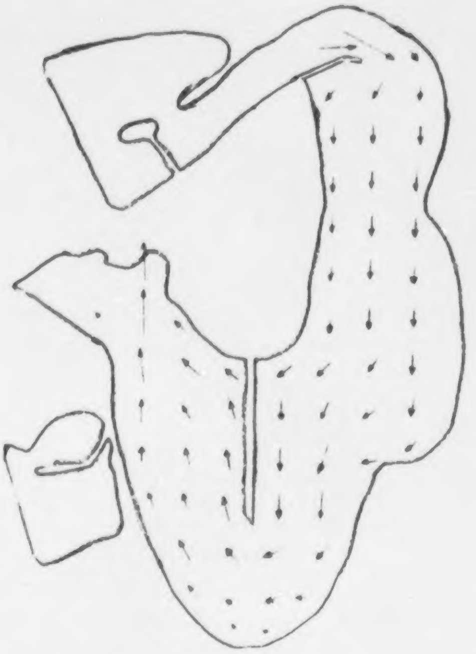

FIGURE C.5(b). VELOCITY FIELD

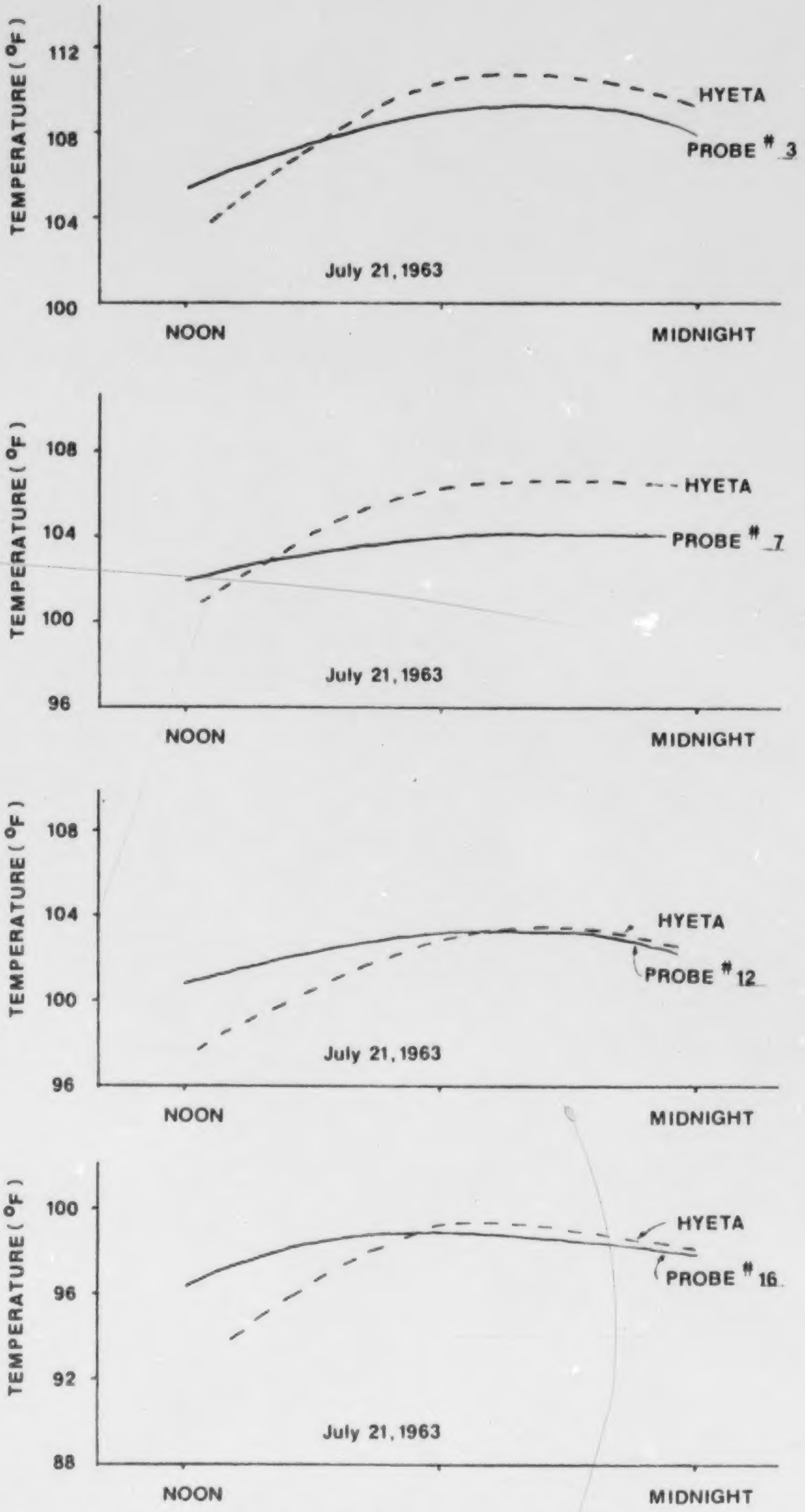

FIGURE C.6. COMPARISON OF RECORDED AND COMPUTED TEMPERATURES - HORSESHOE LAKE

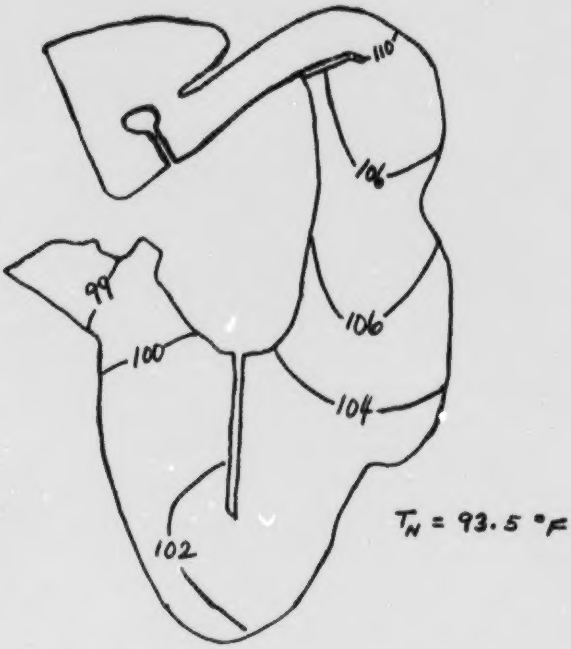

FIGURE C.7. TEMPERATURE DISTRIBUTION ON HORSESHOE LAKE
6:00 p.m. JULY 21, 1963

```
PAGE    1

// JOB    C.6.1   SOURCE LISTING

LOG DRIVE    PACK SPEC    PACK AVAIL   PHY DRIVE      14:43:40      04/09/76
  0000          1830         1830         0000

CMS R01.03    ACTUAL 16K   CONFIG 16K

// FOR       14:43:41      04/09/76
*ONE WORD INTEGERS
*LIST SOURCE PROGRAM
*IOCS(DISK,CARD,1403 PRINTER)
      DIMENSION TITLE(20)
      DIMENSION DOLD(14,16)
      DIMENSION DO(14,16),BOD(14,16),UP(14,16),VP(14,16)
      COMMON H(14,16),Z(14,16),DEPTH(14,16),U(14,16),V(14,16),T(14,16),
     1 R(14,16),HA(14,16),RECOR(30,5),SHRS,DELTA, AHD,AWL,EHS,CG,
     2 EWLE,     SHE,DOS,TF2X,TF2Y,REEWL(14,16),BODLD(14,16),DTDS2,
     3 RNEWL,XKA,XKR,XKD,DTDS,DTCGC,DTCG,CGDS2,CDS2D,BC,BGH,DS2DT,
     4 NPRNT,IMAXM,JMAXM,NPROT,NTYPE
      EQUIVALENCE (DO(1,1),T(1,1)),(BOD(1,1),REEWL(1,1))
      EQUIVALENCE (DOLD(1,1),HA(1,1))
      DATA CP,GAMMA,GRAV,HL/0.998,62.247,32.2,970.3/
      DATA TMIN,HTEMP/2*0.0/
      DATA M/0/
      IN=2
      IOUT=5
      SSHLC=0.0
      SSWLC=0.0
      HRS=0.0
      SHRS=0.0
      AHD=0.0
      AWL=0.0
      EHS=0.0
C
C     INITIALIZE PERMANENT SUMMARY STATISTICS
    1 FORMAT(7I10,I5)
    2 FORMAT(F10.4,I10)
    3 FORMAT(20A4)
    4 FORMAT(5F10.3, 2I10)
    6 FORMAT(I10,F10.3,I10,F10.2)
C
C     READ NUMERICAL PARAMETERS
      READ(IN,3)TITLE
      READ(IN,2)PRNT,NPRNT
      READ(IN,1)NSTEP
C
C     READ BATHYMETRY
      READ(IN,4)DELTS,DELTA
      READ(IN,6) NSTDY,IDELT,NOW,PRNT2
      READ(IN,1)IMAX,JMAX
      NEC = 0
      DO 125 J=1, JMAX
           DO 125 I=1, IMAX
      READ(IN,4)H(I,J),Z(I,J)
      BODLD(I,J)=0.0
                U(I,J) = 0.0
                UP(I,J) = 0.0
                V(I,J) = 0.0
```

```
PAGE   2

                VP(I,J) = 0.0
                T(I,J) = 0.0
                R(I,J) = 0.0
                REEWL(I,J) = 0.0
                HA(I,J) = 0.0
                DEPTH(I,J) = H(I,J) - Z(I,J)
      IF(DEPTH(I,J))121,121,125
  121 DEPTH(I,J)=-100000.0
                NEC = NEC + 1
  125 CONTINUE
      IMAXM=IMAX-1
      JMAXM=JMAX-1
C
C
C     READ METERORLOGY, DIFFUSIVITY, AND FRICTION
      READ(IN,4)W,THETA
      READ(IN,4)PTMAX,DPT,CWS
      READ(IN,4) DIFX,DIFY,F
C
C  INPUTING INFO ON DO-BOD OR TEMP
C  NTYPE = 1  - TEMP
C  NTYPE = 2  - DO-BOD
C
      READ(IN,6) NTYPE
      GO TO (1000,2000),NTYPE
 2000 CONTINUE
      READ(IN,531) XKA,XKD,XKR
  531 FORMAT(3F7.4,F5.1)
      READ(IN,535) BOD0,DO0
  535 FORMAT(2F7.2)
      TEMP=(PTMAX-32.0)*5.0/9.0
      DOS=14.652+TEMP*(-0.41022+TEMP*(0.007991-.000077774*TEMP))
      ADJST=1.047**(TEMP-20.0)
      XKA=XKA*ADJST
      XKR=XKR*ADJST
      XKD=XKD*ADJST
C
C  SETTING INITIAL DO'S + BOD'S
C
      DO 150 I=2,IMAXM
      DO 150 J=2,JMAXM
      DO(I,J)=DO0
      BOD(I,J)=BOD0
  150 CONTINUE
 1000 CONTINUE
C
C     COMPUTE WIND SHEAR TERMS AND METEOROLOGICAL VARIABLES
      VDK = 0.0
      IF(W-14.0)195,195,295
  295 VDK=2.5E-6*(1.0-14.0/W)*(1.0-14.0/W)
  195 VDK = VDK + 1.1E-6
      X=VDK*W*W*COS(THETA)
      Y=VDK*W*W*SIN(THETA)
      APTDP=0.5*(PTMAX+DPT)
      BETA=0.255-.0085*APTDP+0.000204*APTDP*APTDP
      FCWS = 70.0 + 0.7 * CWS * CWS
      CSHE = (15.7 + (BETA + 0.26) * FCWS) / 86400.0
      BC = BETA * (CSHE - 0.00018171296)
```

```
PAGE    3

      BGH=(0.26+BETA)*GAMMA*HL
      RNEWL = BC * (PTMAX - DPT) / BGH
C
C
C     COMPUTE CONVIENIENT CONSTANTS
C     NOTED  THESE VARIABLES ARE DEFINED BELOW ONLY
C
      FDT=F*DELTA
      DTDS=DELTA/DELTS
      GDT2D=GRAV*DTDS/2.0
      XDT=X*DELTA
      YDT=Y*DELTA
      DT4DS = DTDS / 4.0
      DTDS2=DTDS/DELTS
      TF2X=DTDS2*DIFX
      TF2Y=DTDS2*DIFY
      CG = CP * GAMMA
      DTCGC=DELTA*CSHE/CG
      DS2=DELTS*DELTS
      CDS2D=CSHE*DS2*DELTA
      CGDS2 = CG * DS2
      CGC = CSHE / CG
      DTCG=DELTA/CG
      AREA=DS2*FLOAT(JMAX*IMAX-NEC)
      EWLN=AREA*DELTA*RNEWL
      DS2DT=DS2*DELTA
      DDX=DIFX*CG/DS2
      DDY=DIFY*CG/DS2
      NN=IFIX(60.0*PRNT/DELTA+0.5)
      NPROT = 1
      CALL HYETB(TITLE,DELTS,DELTA,NSTEP,PRNT,NPRNT,IMAX,JMAX,AREA,CSHE,
     1 DIFX,DIFY,F,THETA,W,PTMAX,DPT,CWS,NTYPE,XKA,XKD,XKR,RODO,DOO,DOS,
     2 TDELT,NOW)
      GOTO(209,208),NTYPE
  208 XKA=XKA/86400.0
      XKR=XKR/86400.0
      XKR=XKR/86400.0
  209 CONTINUE
C
C
      IF(IMAX-20)212,212,112
  212 WRITE(IOUT,105)
  105 FORMAT('-', 'THE FOLLOWING ARE THE INITIAL DEPTHS.')
      WRITE(IOUT,110)
  110 FORMAT('0')
      CALL GRID(DEPTH,IMAX,JMAX)
  112 CONTINUE
C
C  SET INITIAL BOUNDARY SOURCE/SINK VALUES
C
C    ***************
C    *** INPUT=1 ***
C    ***************
C
C -----------------------------------------------------------------------
      R(2,10) = 2.667E-4
      R(2, 9) = 2.667E-4
      R(2, 8) = 2.667E-4
      R(2, 3) = -8.0E-4
C
C ----------------------------------------------------------------------
C     INTERGATE EQUATIONS OVER DESIRED NUMBER OF TIME INCREMENTS
C
      DO 200 N=1,NSTEP
C
      M = M + 1
      IF(NSTDY) 5002,5002,4999
 4999 IF(N-(NOW+1)) 5000,5001,5002
 5000 DO 350 J=2,JMAXM
      JJ=J+1
      DO 350 I=2,IMAXM
      IF(DEPTH(I,J)) 350,350,194
  194 RN=R(I,J)-RNEWL
      H(I,J)=H(I,J)+DTDS*(U(I,J)+V(I,J)-U(I+1,J)-V(I,JJ) )+DELTA *RN
      DEPTH(I,J)=H(I,J)-Z(I,J)
  350 CONTINUE
      GOTO 2700
 5001 DELTA=TDELT
      M = 1
      PRNT=PRNT2
      DTDS=DELTA/DELTS
      DTDS2=DTDS/DELTS
      TF2X=DTDS2*DIFX
      TF2Y=DTDS2*DIFY
      DTCGC=DELTA*CSHE/CG
      CDS2D=CSHE*DS2*DELTA
      DTCG=DELTA/CG
      DS2DT=DS2*DELTA
      NN=IFIX(60.0*PRNT/DELTA+0.5)
      TMIN=0.0
      WRITE(IOUT,6047)
 6047 FORMAT('1',//,'*** VELOCITY FIELD IS NOW HELD CONSTANT ***')
 5002 CONTINUE
C
C
C  VARIABLES WHICH ARE KNOWN FUNCTIONS OF TIME ARE SPECIFIED HERE
C     SUCH AS - SOURCES/SINKS AT BOUNDARIES
C
C
C  HEAT SOURCES/SINKS
C
C
C   ***************
C   *** INPUT=2 ***
C   ***************
C  ---------------------------------------------------------------------
C
C  HEAT SOURCE
      HA(2, 8) = 0.331
      HA(2, 9) = 0.331
      HA(2,10) = 0.331
      HA(2,3) = CG * R(2,3) * T(2,3)
      HTEMP = 0.993
C  ---------------------------------------------------------------------
C
C
C
```

```
PAGE   5

      GOTO(2500,2600),NTYPE
C
 2500 SHRS=SHRS+HTEMP*DS2DT
      CALL TEMPR(NSTDY)
C
C     INCREMENT PERMANENT SUMMARY STATISTICS
          AHD = AHD + SHE + SSHLC
          AWL = AWL + EWLN + EWLE + SSWLC
      GOTO 2700
 2600 CALL DOBOD(NSTDY)
 2700 CONTINUE
C     DISPLAY RESULTS, IF DESIRED
  520 IF((M/NN)*NN-M) 530,525,530
  525 TMIN=TMIN+PRNT
      CALL DSPLA(N,IMAX,JMAX,TMIN)
  530 CONTINUE
C
      IF(NSTDY) 5005,5005,5004
 5004 IF(N-(NOW+1)) 5005,200,200
 5005 CONTINUE
C     COMPUTE NEW FLOWS PER UNIT WIDTH
C   ***************
C   *** INPUT=3 ***
C   ***************
C  --------------------------------------------------------
      U(3, 8) = 0.1333
      U(3, 9) = 0.1333
      U(3,10) = 0.1333
      U(3, 3) = -0.4
C  --------------------------------------------------------
      DO 300 J=2,JMAXM
      JJ=J+1
      DO 300 I=2,IMAXM
      II=I+1
      DD=DEPTH(I,J)
      DDJ=DEPTH(I,JJ)
      DDI=DEPTH(II,J)
  314 IF(DD       )  300,300,302
  302 IF(DDI            )333,333,304
  304                   ADSQ = V(I,J) + V(II ,J) + V(I,JJ ) + V(II ,JJ )
                        ADSQ = ADSQ * ADSQ
                        ADSQD=DD + DDI
                        ADSQD = ADSQD * ADSQD
                        G = 1.0 + FDT *  SQRT(16.0 * U(II ,J) * U(II ,J)
     2                  + ADSQ) / ADSQD
                        UP(II ,J) = (U(II ,J) + GDT2D  * (DDI
     2      + DD            )*(H(I,J)-H(II ,J))+XDT)/G
  333 IF(DDJ            )300,300,306
  306 ADSQ=U(I,J)+U(II ,J)+U(I,JJ )+U(II ,JJ )
                        ADSQ = ADSQ * ADSQ
                        ADSQD = DD + DDJ
                        ADSQD = ADSQD* ADSQD
                        G = 1.0 + FDT *  SQRT(16.0 * V(I,JJ ) * V(I,JJ )
     2                  + ADSQ) / ADSQD
                        VP(I,JJ ) = (V(I,JJ ) + GDT2D  * (DDJ
     2                  + DD          ) * (H(I,J) - H(I,JJ )) + YDT) / G
  300         CONTINUE
C
```

```
PAGE   6

C      RETURN COMPUTED VALUES TO COMPUTING ARRAYS
       DO 325 J=2,JMAXM
       JJ=J+1
       DO 325 I=2,IMAXM
       II=I+1
   324 U(II,J)=UP(II,J)
   326 V(I,JJ)=VP(I,JJ)
   325      CONTINUE
C
   200 CONTINUE
C
       GOTO(10000,20000),NTYPE
 10000 CONTINUE
       CALL HYETC(NPROT,RECOR)
 20000 CONTINUE
       CALL EXIT
       END

UNREFERENCED STATEMENTS
  320      314      324      326

FEATURES SUPPORTED
 ONE WORD INTEGERS
 IOCS

CORE REQUIREMENTS FOR
 COMMON   4834  VARIABLES   1062  PROGRAM   1730

END OF COMPILATION

// DUP     14:44:45    04/09/76

*DELETE               HYETA
PACK ID 1830   DB ADDR 1B610   DB CNT  00088

*STORE       WS  UA  HYETA
PACK ID 1830   DB ADDR 1B610   DB CNT  00081
```

```
// JOB

LOG DRIVE   PACK SPEC   PACK AVAIL  PHY DRIVE    13:28:44    07/28/75
  0000        1830        1830        0000

CMS R01.03   ACTUAL 16K  CONFIG 16K

// FOR     13:28:46    07/28/75
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE HYETB(TITLE,DELTS,DELTA,NSTEP,PRNT,NPRNT,IMAX,JMAX,
     1 AREA,CSHE,DIFX,DIFY,F,THETA,W,PTMAX,DPT,CWS,NTYPE,XKA,XKD,XKR,
     2 BODO,DOO,DOS,TDELT,NOW)
      DIMENSION TITLE(20)
C     PRINT INITIAL INFORMATION
      IOUT=5
      WRITE(IOUT,50)TITLE
   50 FORMAT('1',/////,20A4)
      WRITE(IOUT,70)
   70 FORMAT('-', 'THE FOLLOWING ARE THE PARAMETERS OF THE NUMERICAL SCH
     CEME.')
      WRITE(IOUT,75)DELTS
   75 FORMAT('0', 'DELTAS = ', F9.2, ' FEET')
      WRITE(IOUT,80)DELTA
   80 FORMAT(' ', 'DELTAT = ', F9.2, ' SEC')
      WRITE(IOUT,85)NSTEP
   85 FORMAT(' ', 'NSTEPS = ', I6)
      WRITE(IOUT,90)PRNT
   90 FORMAT(' ', 'PRNT = ', F11.2, ' MIN')
      WRITE(IOUT,115)NPRNT
  115 FORMAT(' ', 'NPRNT = ',I7)
      WRITE(IOUT,95)IMAX
   95 FORMAT(' ', 'IMAX = ', I8)
      WRITE(IOUT,100)JMAX
  100 FORMAT(' ', 'JMAX = ', I8)
      WRITE(IOUT,105) TDELT,NOW
  105 FORMAT(' ','TDELT = ',F8.2,' SEC',/,' NOW = ',I10)
      WRITE(IOUT,5)
    5 FORMAT('-', 'THE FOLLOWING ARE THE VALUES OF THE CONSTANTS USED IN
     C THIS SIMULATION.')
      WRITE(IOUT,10)
   10 FORMAT('0', 'SYMBOLIC NAME', 5X, 'CONSTANT', 23X, 'VALUE', 10X, 'U
     CNITS')
      WRITE(IOUT,15)
   15 FORMAT('+',     5X, '             ', 23X, '     ', 10X, '
     C     ')
      WRITE(IOUT,20)AREA
   20 FORMAT('0', 'AREA', 14X, 'SURFACE AREA', 19X, E10.3, 5X, 'FT**2')
      WRITE(IOUT,35) DIFX,DIFY
   35 FORMAT(' ','DIFX',14X,'DIFFUSIVITY',20X,F10.5,5X,'FT**2/SEC'
     1 ,/,' DIFY',45X,F10.5,5X,'FT**2/SEC')
      WRITE(IOUT,45)F
   45 FORMAT(' ', 'F', 17X, 'BED RESISTANCE COEFFICIENT', 5X, F10.5, 5X
     C'DIMENSIONLESS')
      WRITE(IOUT,60)THETA
   60 FORMAT(' ', 'THETA', 13X, 'WIND DIRECTION', 17X, F10.5, 5X, 'RADIA
     CNS')
      WRITE(IOUT,65)W
   65 FORMAT(' ', 'W', 17X, 'WIND SPEED', 21X, F10.5, 5X, 'KNOTS')
      WRITE(IOUT,6000)PTMAX
 6000 FORMAT(' ','PTMAX',13X,'POND TEMP',22X,F10.5,5X,'DEGREE F')
      GO TO (2200,2300),NTYPE
 2200 CONTINUE
      WRITE(IOUT,25)
   25 FORMAT(' ', 'CSHE', 14X, 'COEFFICIENT OF SURFACE')
      WRITE(IOUT,30)CSHE
   30 FORMAT(' ', 23X, 'HEAT EXCHANGE', 13X, F10.5, 5X, 'BTU/FT**2 SEC D
     CEGREE F')
      WRITE(IOUT,6005)DPT
 6005 FORMAT(' ','DPT',15X,'DEW POINT TEMP',17X,F10.5,5X,'DEGREE F')
      WRITE(IOUT,6010)CWS
 6010 FORMAT(' ','CWS',15X,'COOLING WIND SPEED',13X,F10.5,5X,'MPH')
      GOTO 2400
 2300 CONTINUE
      WRITE(IOUT,6050) XKA,XKR,XKD
 6050 FORMAT(' ','KA',16X,'COEFF OF SURFACE RE-AERATION',5X,F5.2,8X,
     1 '1/DAY',/,' KR',16X,'COEFF OF BOD REMOVAL',13X,F5.2,8X,'1/DAY'
     2 /,' KD',16X,'COEFF OF OXYGEN UTILIZATION',6X,F5.2,8X,'1/DAY')
      WRITE(IOUT,6060) BODO,DOO,DOS
 6060 FORMAT(' ','BODO',14X,'INITIAL BOD',20X,F7.2,8X,'PPM',/,
     1 ' DOO',15X,'INITIAL DO',21X,F7.2,8X,'PPM',/,
     2 ' DOS',15X,'SAT.DO',25X,F7.2,8X,'PPM')
 2400 CONTINUE
      RETURN
      END

FEATURES SUPPORTED
 ONE WORD INTEGERS

CORE REQUIREMENTS FOR HYETB
 COMMON       0  VARIABLES      2  PROGRAM    830

RELATIVE ENTRY POINT ADDRESS IS 0260 (HEX)

END OF COMPILATION

// DUP      13:29:04    07/28/75

*DELETE              HYETB
PACK ID 1830   DB ADDR 1B860   DB CNT  00033

*STORE       WS  UA  HYETB
PACK ID 1830   DB ADDR 1B971   DB CNT  00035
```

```
PAGE   1

// JOB

LOG DRIVE   PACK SPEC   PACK AVAIL  PHY DRIVE    17:26:51    07/22/75
  0000        1830        1830        0000

CMS R01.03   ACTUAL 16K  CONFIG 16K

// FOR      17:26:56    07/22/75
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE HYETC(NPROT,RECOR)
      DIMENSION RECOR(30,5)
C     PRINT SUMMARY STATISTICS
      IOUT=5
      NPROT = NPROT - 1
      WRITE(IOUT,400)
  400 FORMAT('1', 'TIME,', 5X, 'TOTAL', 8X, 'TOTAL', 9X, 'HEAT', 9X,
     2 'TOTAL')
      WRITE(IOUT,405)
  405 FORMAT('+', 63X, '                                      ')
      WRITE(IOUT,410)
  410 FORMAT(' ', 'HOURS', 5X, 'HEAT', 9X, 'HEAT', 10X, 'STORED,', 6X,
     2 'WATER')
      WRITE(IOUT,415)
  415 FORMAT('+', '      ')
      WRITE(IOUT,420)
  420 FORMAT(' ',10X, 'LOAD,', 8X, 'DISSIPATED,', 3X, 'BTU', 10X,
     2 'LOSS,')
      WRITE(IOUT,425)
  425 FORMAT('+', 37X, '   ')
      WRITE(IOUT,430)
  430 FORMAT(' ', 10X, 'BTU', 10X, 'BTU', 24X, 'FT**3')
      WRITE(IOUT,435)
  435 FORMAT('+', 10X, '   ', 10X, '   ', 24X, '     ')
      DO 890 M=1,NPROT
      WRITE(IOUT,440)(RECOR(M,L),L=1,5)
  890 CONTINUE
  440 FORMAT('0', F7.2, 3X, E10.3, 3X, E10.3, 4X, E10.3, 3X, E10.3)
      RETURN
      END

FEATURES SUPPORTED
 ONE WORD INTEGERS

CORE REQUIREMENTS FOR HYETC
 COMMON      0  VARIABLES       4  PROGRAM    248

RELATIVE ENTRY POINT ADDRESS IS 00A1 (HEX)

END OF COMPILATION

// DUP      17:27:04    07/22/75

*DELETE            HYETC
D 26 NAME NOT FOUND IN LET/FLET


*STORE      WS  UA  HYETC
```

```
// JOB

LOG DRIVE   PACK SPEC   PACK AVAIL  PHY DRIVE    08:41:19    08/11/75
  0000        1830        1830        0000

CMS R01.03   ACTUAL 16K  CONFIG 16K

// FOR      08:41:20    08/11/75
*ONE WORD INTEGERS
*LIST SOURCE PROGRAM
      SUBROUTINE DSPLA (N,NA,NB,TMIN)
C
C  THIS ROUTINE DISPLAYS VELOCITY + DEPTH INFO AS WELL AS
C       EITHER  TEMP OR BOD-DO
C
      DIMENSION DO(14,16),BOD(14,16)
      DIMENSION TX(14,16),DOX(14,16),BODX(14,16),UX(14,16),VX(14,15)
      COMMON H(14,16),Z(14,16),DEPTH(14,16),U(14,16),V(14,16),T(14,16),
     1 R(14,16),HA(14,16),RECOR(30,5),SHRS,DELTA, AHD,AWL,EHS,CG,
     2 EWLE,     SHE,DOS,TF2X,TF2Y,REEWL(14,16),BODLD(14,16),DTDS2,
     3 RNEWL,XKA,XKR,XKD,DTDS,DTCGC,DTCG,CGDS2,CDS2D,BC,BGH,DS2DT,
     4 NPRNT,IMAXM,JMAXM,NPROT,NTYPE
      EQUIVALENCE (DO(1,1),T(1,1)),(BOD(1,1),REEWL(1,1))
      EQUIVALENCE (TX(1,1),DOX(1,1),UX(1,1)),(BODX(1,1),VX(1,1))
      DATA IOUT/5/
      WRITE(IOUT,61) TMIN,N
   61 FORMAT('1',/,6X,'SIMULATED TIME =',F8.2,'MINS',/,6X,
     1 'ITERATIONS =',I5,/)
C
C  ADJUSTING FLOWS/UNIT WIDTH FOR OUTPUT
C
      DO 71 J=1,NB
      DO 71 I=1,NA
      UX(I,J)=U(I,J)/DEPTH(I,J)
      VX(I,J)=V(I,J)/DEPTH(I,J)
   71 CONTINUE
      WRITE(IOUT,611)
  611 FORMAT('0',5X,'** VELOCITY COMPONENT IN U DIRECTION (FT/SEC) **',
     1/)
      CALL GRID(UX,NA,NB)
      WRITE(IOUT,612)
  612 FORMAT('0',5X,'** VELOCITY COMPONENT IN V DIRECTION (FT/SEC) **',
     1/)
      CALL GRID(VX,NA,NB)
C
C  PRINTING DEPTHS
C
      WRITE(IOUT,630)
  630 FORMAT('0',/,6X,'*** DEPTHS(FT) ***',/)
      CALL GRID(DEPTH,NA,NB;
C
C  ADJUSTING + PRINTING TEMPERATURES IF REQUESTED
      GOTO(1000,2000),NTYPE
 1000 DO 120 J=1,NB
      DO 120 I=1,NA
      TX(I,J)=T(I,J)
      IF(DEPTH(I,J)) 119,119,120
  119 TX(I,J) = -100000.0
  120 CONTINUE
      WRITE(IOUT,640)
  640 FORMAT('0',5X,'*** EXCESS TEMPERATURES(DEGREES F) ***',/)
      CALL GRID(TX,NA,NB)
      THR=TMIN/60.0
      RECOR(NPROT,1)=THR
      RECOR(NPROT.2)=SHRS
      RECOR(NPROT,3)=AHD
      RECOR(NPROT,4)=EHS
      RECOR(NPROT,5)=AWL
      NPROT=NPROT+1
      RETURN
C
C  ADJUSTING + PRINTING BOD-DO IF REQUESTED
 2000 CONTINUE
      DO 170 J=1,NB
      DO 170 I=1,NA
      IF(DEPTH(I,J)) 149,149,150
  149 DOX(I.J)= -100000.0
      BODX(I,J)=-100000.0
      GOTO 170
  150 DOX(I,J)=DO(I,J)
      BODX(I,J)=BOD(I,J)
  170 CONTINUE
      WRITE(IOUT,650)
  650 FORMAT('0',5X,'*** DISSOLVED OXYGEN(MG/L) ***',/)
      CALL GRID(DOX,NA,NB)
      WRITE(IOUT,660)
  660 FORMAT('0',5X,'*** BIOCHEM.OXYGEN DEMAND(MG/L) ***',/)
      CALL GRID(BODX,NA,NB)
      RETURN
      END

FEATURES SUPPORTED
 ONE WORD INTEGERS

CORE REQUIREMENTS FOR DSPLA
 COMMON   4834  VARIABLES    906  PROGRAM    516

RELATIVE ENTRY POINT ADDRESS IS 043E (HEX)

END OF COMPILATION

// DUP      08:41:38    08/11/75

*DELETE              DSPLA
PACK ID 1830   DB ADDR 1B0EF   DB CNT  00035

*STORE       WS  UA  DSPLA
PACK ID 1830   DB ADDR 1BF97   DB CNT  00022
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FORTRAN IV G LEVEL  21                    GRID                DATE = 75156

 0001                SUBROUTINE GRID(A,NC,ND)
           C
           C         SUBROUTINE GRID PRINTS A GRID OF LENTH NA AND WIDTH NB.
           C
 0002                IMPLICIT REAL*8 (A-H,O-Z)
 0003                DIMENSION A(20,20)
 0004                DO 100 K=1,ND
 0005                J=ND-K+1
 0006                WRITE(6,10)(A(I,J),I=1,NC)
 0007            100 CONTINUE
 0008             10 FORMAT(' ', 20F6.2)
 0009                RETURN
 0010                END
```

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// JOB

LOG DRIVE   PACK SPEC   PACK AVAIL  PHY DRIVE    16:27:14    07/28/75
  0000        1830        1830        0000

CMS R01.03   ACTUAL 16K  CONFIG 16K

// FOR      16:27:15    07/28/75
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE TEMPR(NSTDY)
      DIMENSION TP(14,16)
      COMMON H(14,16),Z(14,16),DEPTH(14,16),U(14,16),V(14,16),T(14,16),
     1 R(14,16),HA(14,16),RECOR(30,5),SHRS,DELTA, AHD,AWL,EHS,CG,
     2 EWLE,     SHE,DOS,TF2X,TF2Y,REEWL(14,16),BODLD(14,16),DTDS2,
     3 RNEWL,XKA,XKR,XKD,DTDS,DTCGC,DTCG,CGDS2,CDS2D,BC,BGH,DS2DT,
     4 NPRNT,IMAXM,JMAXM,NPROT,NTYPE
      DATA TP/224*0.0/
C     INITIALIZE TIME STEP SUMMARY STATISTICS
  530 EHS=0.0
            EWLE = 0.0
            SHE = 0.0
C
C     COMPUTE NEW HEIGHTS AND TEMPERATURES
      DO 350 J=2,JMAXM
      DO 350 I=2,IMAXM
      IF(DEPTH(I,J)) 350,350,311
  311 IF(NSTDY) 331,331,195
  331 RN     =R(I,J)-RNEWL-REEWL(I,J)
                    H(I,J) = H(I,J) + DTDS * (U(I,J) + V(I,J)
     2 -U(I+1,J) - V(I,J+1)) + DELTA*RN
                    DEPTH(I,J) = H(I,J) - Z(I,J)
  195 IF(DEPTH(I+1,J))334,334,335
  334 T(I+1,J)=T(I,J)
  335 IF(DEPTH(I-1,J))337,337,339
  337 T(I-1,J)=T(I,J)
  339 IF(DEPTH(I,J+1))341,341,345
  341 T(I,J+1)=T(I,J)
  345 IF(DEPTH(I,J-1))347,347,349
  347 T(I,J-1)=T(I,J)
C
C                FLOW DIRECTION SENSING TECHNIQUE
C
  349 BETAX=0.0
      BETAY=0.0
      ALFAX=0.0
      ALFAY=0.0
      U1=U(I,J)
      U2=U(I+1,J)
      V1=V(I,J)
      V2=V(I,J+1)
      IF(U1) 7010,7010,7000
 7000 ALFAX=1.0
 7010 IF(U2) 7030,7030,7020
 7020 BETAX=1.0
 7030 IF(V1) 7050,7050,7040
 7040 ALFAY=1.0
 7050 IF(V2) 7070,7070,7060
 7060 BETAY=1.0
 7070 CONTINUE
C
C  CALCULATING TEMPERATURE
C
      C1=1.0-(DTDS/DEPTH(I,J))*(BETAX*U2-(1.0-ALFAX)*U1
     1 +BETAY*V2-(1.0-ALFAY)*V1)-2.0*(TF2X+TF2Y)-DTCGC/DEPTH(I,J)
      C2=TF2X-DTDS*(1.0-BETAX)*U2/DEPTH(I,J)
      C3=DTDS*ALFAX*U1/DEPTH(I,J)+TF2X
      C4=TF2Y-(1.0-BETAY)*DTDS*V2/DEPTH(I,J)
      C5=TF2Y+DTDS*ALFAY*V1/DEPTH(I,J)
      TP(I,J)=C1*T(I,J)+C2*T(I+1,J)+C3*T(I-1,J)+C4*T(I,J+1)+
     1 C5*T(I,J-1)+DTCG*HA(I,J)/DEPTH(I,J)
C
  350 CONTINUE
C
C
C     RETURN COMPUTED TEMPERATURES TO COMPUTING ARRAY AND
C     INCREMENT SUMMARY STATISTICS
      DO 375 J=2,JMAXM
      DO 375 I=2,IMAXM
  412 IF(DEPTH(I,J))375,375,371
  371 IF(ABS(TP(I,J))-1.0E-35)372,373,373
  372 TP(I,J)=0.0
  373 T(I,J)=TP(I,J)
                     EHS = EHS + CGDS2 * DEPTH(I,J) * T(I,J)
                     SHE = SHE + CDS2D  * T(I,J)
                     REEWL(I,J) = BC * T(I,J) / BGH
                     EWLE = EWLE + DS2DT * REEWL(I,J)
  375 CONTINUE
      RETURN
      END

UNREFERENCED STATEMENTS
 530     412

FEATURES SUPPORTED
 ONE WORD INTEGERS

CORE REQUIREMENTS FOR TEMPR
 COMMON   4834  VARIABLES     496  PROGRAM     684

RELATIVE ENTRY POINT ADDRESS IS 01F9 (HEX)

END OF COMPILATION

// DUP     16:27:43    07/28/75

*DELETE             TEMPR
PACK ID 1830   DB ADDR 1B8E9   DB CNT  0004D

*STORE      WS  UA  TEMPR
PACK ID 1830   DB ADDR 1B959   DB CNT  0004D
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// JOB

LOG DRIVE   PACK SPEC   PACK AVAIL  PHY DRIVE    16:27:47    07/28/75
  0000        1830        1830         0000

CMS R01.03   ACTUAL 16K  CONFIG 16K

// FOR      16:27:49    07/28/75
*LIST SOURCE PROGRAM
*ONE WORD INTEGERS
      SUBROUTINE DOBOD(NSTDY)
C
C  THIS ROUTINE CALCULATES HEIGHTS + DO-BOD FOR NEXT TIME STEP
C
C  COMPUTE HEIGHTS + DO-BOD'S
C
      DIMENSION DO(14,16),BOD(14,16)
      DIMENSION DOP(14,16),BODP(14,16),DOLD(14,16)
      COMMON H(14,16),Z(14,16),DEPTH(14,16),U(14,16),V(14,16),T(14,16),
     1 R(14,16),HA(14,16),RECOR(30,5),SHRS,DELTA, AHD,AWL,EHS,CG,
     2 EWLE,    SHE,DCS,TF2X,TF2Y,REEWL(14,16),BODLD(14,16),DTDS2,
     3 RNEWL,XKA,XKR,XKD,DTDS,DTCGC,DTCG,CGDS2,CDS2D,BC,BGH,DS2DT,
     4 NPRNT,IMAXM,JMAXM,NPROT,NTYPE
      EQUIVALENCE (DO(1,1),T(1,1)),(BOD(1,1),REEWL(1,1))
      EQUIVALENCE (DOLD(1,1),HA(1,1))
      DATA DOP,BODP/448*0.0/
      C1B=-DELTA*XKR
      C1C=-DELTA*XKA
      DO 350 J=2,JMAXM
      DO 350 I=2,IMAXM
      IF(DEPTH(I,J)) 350,350,192
  192 IF(NSTDY) 194,194,195
  194 RN=R(I,J)-RNEWL
      H(I,J)=H(I,J)+DTDS*(U(I,J)+V(I,J)-U(I+1,J)-V(I,J+1))+DELTA *RN
      DEPTH(I,J)=H(I,J)-Z(I,J)
  195 IF(DEPTH(I+1,J)) 196,196,200
  196 DO(I+1,J)=DO(I,J)
      BOD(I+1,J)=BOD(I,J)
  200 IF(DEPTH(I-1,J)) 201,201,210
  201 DO(I-1,J)=DO(I,J)
      BOD(I-1,J)=BOD(I,J)
  210 IF(DEPTH(I,J+1)) 212,212,220
  212 DO(I,J+1)=DO(I,J)
      BOD(I,J+1)=BOD(I,J)
  220 IF(DEPTH(I,J-1)) 222,222,230
  222 DO(I,J-1)=DO(I,J)
      BOD(I,J-1)=BOD(I,J)
  230 CONTINUE
C  J.EDINGER'S FLOW DIRECTION SENSING TECHNIQUE (JULY 1/75)
C
      BETAX=0.0
      BETAY=0.0
      ALFAX=0.0
      ALFAY=0.0
      U1=U(I,J)
      U2=U(I+1,J)
      V1=V(I,J)
      V2=V(I,J+1)
      IF(U1) 7010,7010,7000
 7000 ALFAX=1.0
 7010 IF(U2) 7030,7030,7020
 7020 BETAX=1.0
 7030 IF(V1) 7050,7050,7040
 7040 ALFAY=1.0
 7050 IF(V2) 7070,7070,7060
 7060 BETAY=1.0
 7070 CONTINUE
C
C
      C1A=1.0-(DTDS/DEPTH(I,J))*(BETAX*U2-(1.0-ALFAX)*U1+BETAY*V2
     1 -(1.0-ALFAY)*V1)-2.0*(TF2X+TF2Y)
      C2=TF2X-DTDS*(1.0-BETAX)*U2/DEPTH(I,J)
      C3=DTDS*ALFAX*U1/DEPTH(I,J)+TF2X
      C4=TF2Y-(1.0-BETAY)*DTDS*V2/DEPTH(I,J)
      C5=TF2Y+DTDS*ALFAY*V1/DEPTH(I,J)
C  CALCULATING BOD
      C1=C1A
      VAL=0.0
      IF(DO(I,J)-2.0) 349,349,348
  348 C1=C1+C1B
      VAL=XKD*BOD(I,J)
  349 CONTINUE
      BODP(I,J)=C1*BOD(I,J) +C2*BOD(I+1,J) + C3*BOD(I-1,J) + C4*BOD(I,J
     1 +1) + C5*BOD(I,J-1)+ DELTA*BODLD(I,J)*R(I,J)/DEPTH(I,J)
C  CALCULATING DO
      C1=C1A+C1C
      DOP(I,J)= C1*DO(I,J) + C2*DO(I+1,J) + C3*DO(I-1,J)
     1 + C4*DO(I,J+1) + C5*DO(I,J-1)
     2 +DELTA*(XKA*DOS- VAL         +DOLD(I,J)*R(I,J)/DEPTH(I,J))
C
  350 CONTINUE
C
C  BOOKKEEPING LOOP
C
      DO 375 J=2,JMAXM
      DO 375 I=2,IMAXM
      IF(DEPTH(I,J)) 375,375,370
  370 DP=DOP(I,J)
      IF(DOS-DP) 371,372,376
  376 IF(DP) 377,372,372
  377 DP=0.0
      GOTO 372
  371 DP=DOS
  372 BP=BODP(I,J)
      IF(BP) 373,374,374
  373 BP=0.0
  374 DO(I,J)=DP
      BOD(I,J)=BP
  375 CONTINUE
      RETURN
      END

FEATURES SUPPORTED
 ONE WORD INTEGERS

CORE REQUIREMENTS FOR DOBOD
 COMMON     4834  VARIABLES       956  PROGRAM      814
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APPENDIX D

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